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POSSIBLE IMPACTS OF CLIMATIC WARMING SCENARIOS ON WATER RESOURCES IN THE SASKATCHEWAN RIVER SUBBASIN

by

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ATMOSPHERIC ENVIRONMENT SERVICE

National Hydrology Research Centre
Saskatoon, Saskatchewan

1989

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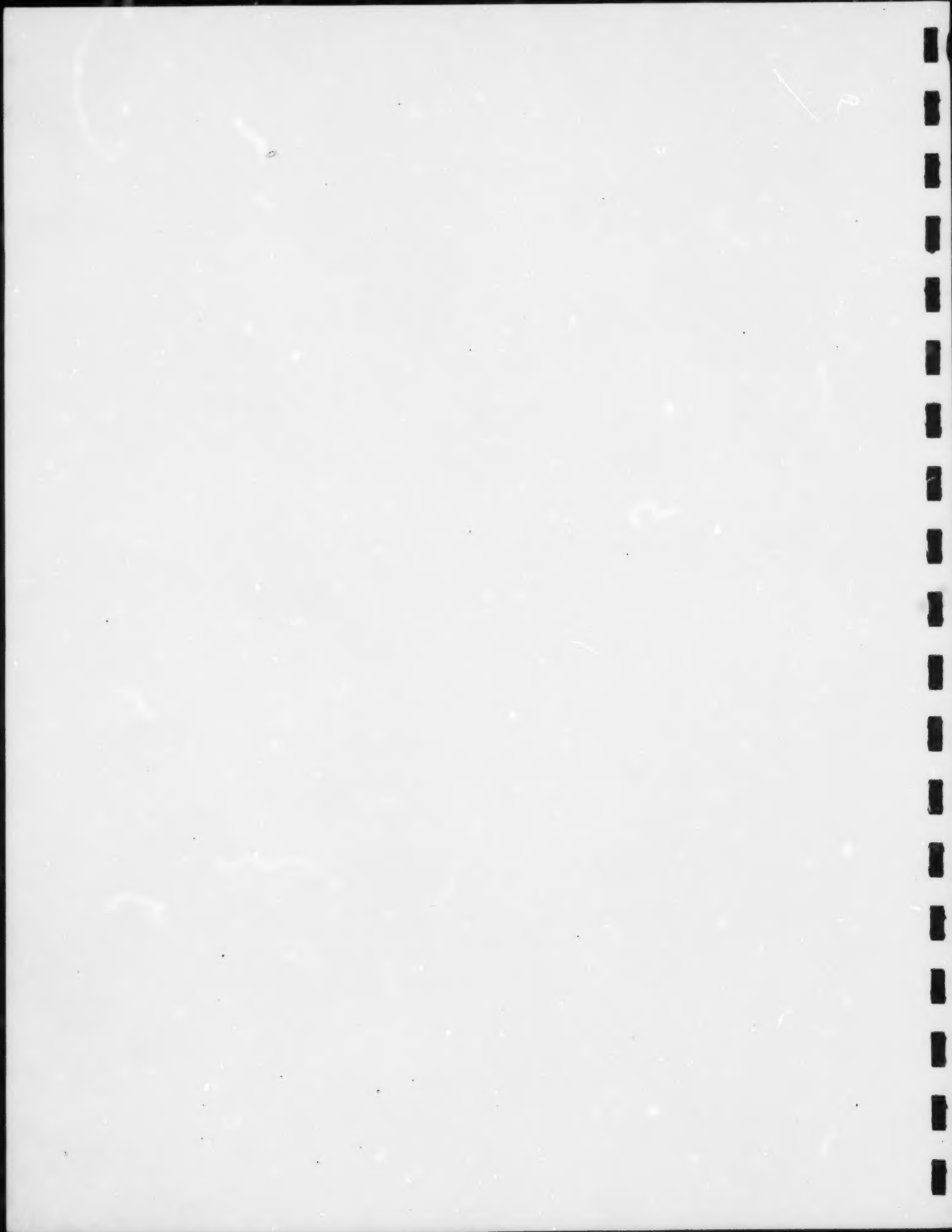
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ABSTRACT

Regional scale studies of the impacts of global warming scenarios provide a useful mechanism for identifying potential regional sensitivities, data gaps and research needs, and for raising awareness of the global warming issue at the regional level. Thus, a pilot study of water resources in the Saskatchewan River Subbasin was undertaken in order to test a Thornthwaite-based methodology, to provide first-cut estimates of impacts in this region, and to identify future research needs. Ten scenarios were constructed, using two hypothetical growth rates for irrigation and output from five General Circulation Models. During the course of this study, a number of methodological questions were raised, including the representativeness of data points, interpolation of observed and scenario data, and the quantification of uncertainty.

Results indicated decreases in summer soil moisture, but no consensus on changes in runoff or annual net basin supply, primarily due to differences in scenario output at the Rocky Mountains, the major source region for runoff. There were a number of recommendations for follow-up research and monitoring.

RÉSUMÉ

Les études à l'échelon régional sur les scénarios de répercussions du réchauffement global constituent un mécanisme utile pour l'identification des éléments vulnérables potentiels par région, des lacunes de données et des besoins en recherche ainsi que pour sensibiliser la population des régions aux questions de réchauffement global. Ainsi, une étude-pilote des ressources hydriques dans le sous-bassin de la rivière Saskatchewan a été entreprise afin de tester une méthodologie basée sur les principes de Thornthwaite, pour fournir des estimations préliminaires concernant les répercussions dans cette région et pour déterminer les besoins en recherche dans l'avenir. Dix scénarios ont été échaudés en faisant appel à deux vitesses de croissance hypothétique pour l'irrigation et les résultats de cinq modèles de circulation générale. Au cours de l'étude, un certain nombre de questions de méthodologie ont été soulevées, notamment la représentativité des points de données, l'interpolation des données observées et des données de scénario ainsi que la quantification de l'incertitude.

Les résultats ont révélé une baisse dans l'humidité des sols en été, mais aucun consensus sur l'évolution du ruissellement ou de l'approvisionnement net annuel des bassins, principalement en raison des différences dans les résultats des scénarios dans les Rocheuses, la principale région à fournir les eaux de ruissellement. Un certain nombre de recommandations ont été faites concernant les recherches complémentaires et la surveillance.

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The views expressed herein are those of the authors and are not necessarily those of Environment Canada.

PREFACE

The Canadian Climate Centre is in the process of developing a capability to assess the biophysical impacts of climatic change. As part of its mandate to study climate and water resources in western Canada, and to support the Canadian Climate Program objectives, the Hydrometeorological Research Division of the Canadian Climate Centre launched a study to examine the implications of climatic change scenarios for runoff in a major prairie watershed. Fortunately, expertise for undertaking such a study already existed in both the Analysis and Impacts and the Hydrometeorology and Marine Divisions of the Canadian Climate Centre. Consequently, a collaborative study was undertaken involving the three Divisions. The contributions and leadership of Dr. Stewart Cohen of the Analysis and Impacts Division were particularly important in planning and executing this study.

The study approach involved the application of techniques, which Dr. Cohen had successfully used in the Great Lakes Basin, to the Saskatchewan River watershed. He was aided in completing this task by Mr. Paul Louie who carried out the objective analysis for temperature and precipitation fields for different climatic change scenarios and Mr. Leslie Welsh who completed an analysis of effective drainage areas and assessed the adequacy of the gridded climatic normals used in the study.

Impact scenarios of the type shown in this report are often criticized because of the uncertainty associated with the general circulation model scenarios. It is clear from the variability between the scenarios presented here that we are not in a position to make categorical statements about the effect of climatic change on flows in the Saskatchewan River. However, the report does contribute to our understanding of the strengths and weaknesses of a frequently used methodology which can be applied to assess the climate/runoff relationships. It also identifies the scientific and modelling problems which must be addressed before we will have a fully reliable method for assessing climatic change impacts on water resources.

Readers who wish to discuss future research opportunities in this area are encouraged to contact the authors or the undersigned.

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ACRONYMS AND INITIALISMS

DEF	Climatic Water <u>D</u> eficit
EID	<u>E</u> astern <u>I</u> rrigation <u>D</u> istrict
GCM	<u>G</u> lobal <u>C</u> irculation <u>M</u> odel
GISS	<u>G</u> oddard <u>I</u> nstitute for <u>S</u> pace <u>S</u> tudies
GFDL	<u>G</u> eophysical <u>F</u> luid <u>D</u> ynamics <u>L</u> aboratory
OSU	<u>O</u> regon <u>S</u> tate <u>U</u> niversity
NBS	<u>N</u> et <u>B</u> asin <u>S</u> upply
PE	<u>P</u> otential <u>E</u> vaporation
PEWTDEF	<u>P</u> otential <u>E</u> vaporation <u>W</u> eighted <u>D</u> EF
PPWB	<u>P</u> rairie <u>P</u> rovinces <u>W</u> ater <u>B</u> oard
SE	<u>S</u> tandard <u>E</u> rror
SIG	<u>L</u> evel of <u>S</u> ignificance
USA	<u>U</u> nited <u>S</u> tates of <u>A</u> merica
U.S. NRC	<u>U</u> nited <u>S</u> tates <u>N</u> ational <u>R</u> esearch <u>C</u> ouncil
WMO	<u>W</u> orld <u>M</u> eteorological <u>O</u> rganization

1 INTRODUCTION

The Saskatchewan River Sub-basin is a major contributor to the flow of the Saskatchewan-Nelson Basin, the largest drainage area in the Prairie Provinces of Canada. The sub-basin area is about 364,000 km², with a 1951-1980 mean annual natural flow of about 650 m³/s at The Pas, Manitoba (Figure 1). This represents approximately one-third of the main basin's drainage area and natural flow, respectively.

The sub-basin includes the North and South Saskatchewan, Red Deer and Bow Rivers (Figure 1), and the Oldman River located south of the Bow River. Most of this flow originates as snowmelt from the Rocky Mountains along the border between Alberta and British Columbia. Very little runoff is contributed from the remainder of the sub-basin, particularly the southern half which has a grassland climate.

East of The Pas, water from the Saskatchewan River Sub-basin mixes with runoff from the Shield area north and east of Lake Winnipeg, and a small amount of flow from southern Saskatchewan and Manitoba. This combined discharge flows northeastward via the Nelson River, eventually draining into Hudson's Bay. The Nelson has been developed for production of hydro-electric power, which is transmitted to markets in southern Manitoba and elsewhere (PPWB, 1982).

Recent projections of global climatic change, based on output from atmospheric General Circulation Model (GCM) experiments, have indicated that increased concentrations of CO₂ and other trace gases could cause a global warming of 1.5°C to 4.5°C by the middle of the twenty-first century (U.S. NRC, 1982; WMO, 1986). Major alterations in regional hydrologic cycles may be an important effect of this warming (Gleick, 1987a). Consequently, the water resources sector, which is very sensitive to climatic variations (Beran, 1986; Chen and Parry, 1987), may be forced to respond in many localities to events that could be outside of historical experience for physical systems (e.g. reservoirs) and institutions (e.g. river basin commissions).

A number of regional case studies of North America, using GCM-based scenarios of global warming as input to the Thornthwaite water budget model (Mather, 1978), have been undertaken for areas including the Great Lakes (Cohen, 1986, 1987b), the Sacramento River Basin of California (Gleick, 1987a,b), the James Bay region of Quebec (Singh, 1987), and four rectangular areas extending from northern Mexico through the United States and into south central Canada (Mather and Feddema, 1986). Estimates of changes in annual runoff have varied regionally, depending largely on the various GCMs' projections of precipitation. Although GCMs show some agreement in 2 x CO₂ scenario temperature changes, considerable regional differences have been

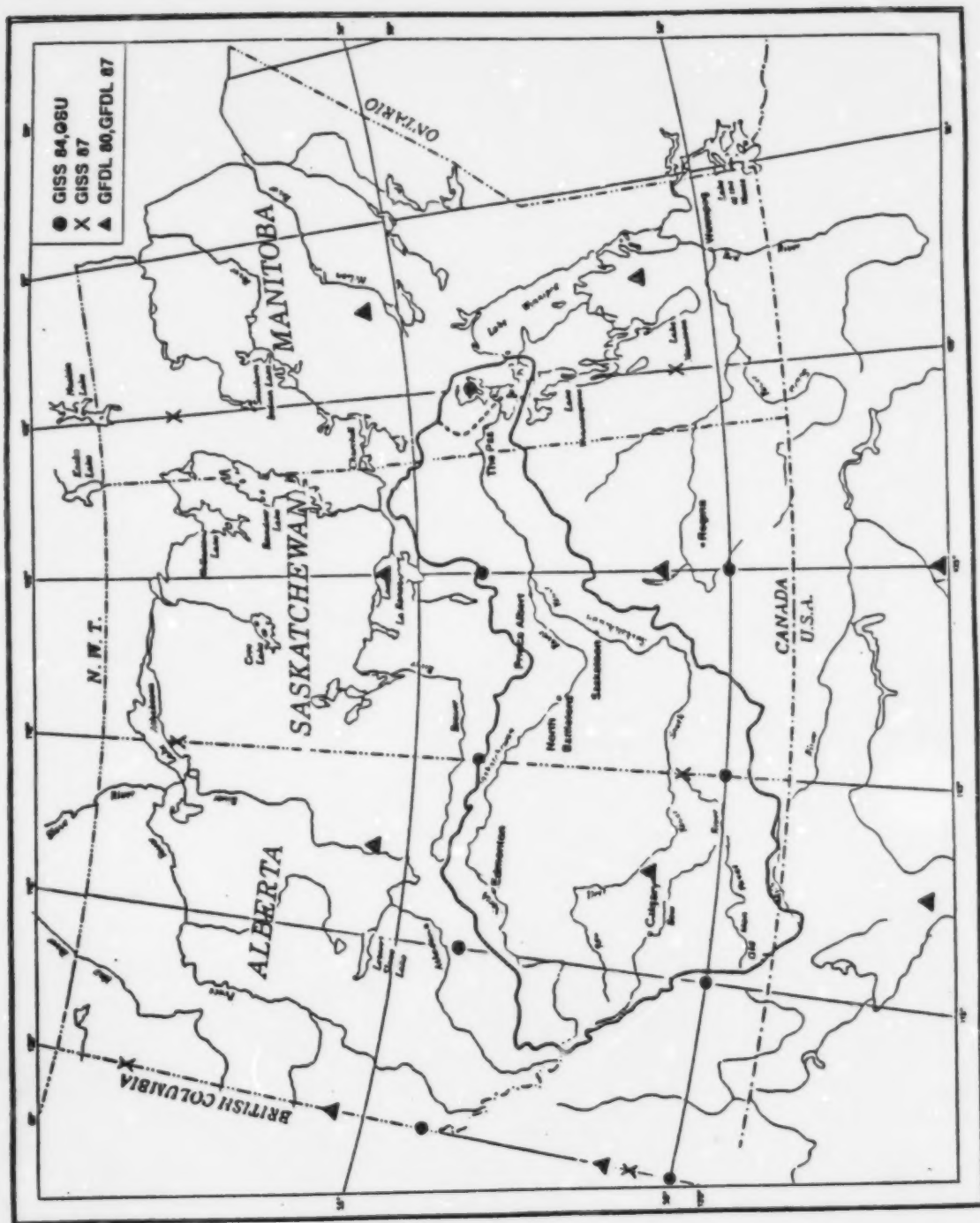


Figure 1--Saskatchewan River Sub-basin

Saskatchewan River sub-basin and surrounding region, including locations of grid points. Dashed line shows the boundary of the sub-basin upstream of the hydrometric station at The

shown for precipitation and soil moisture (Schlesinger and Mitchell, 1985). Such differences have also been demonstrated for a number of experiments using one GCM with different grid spacings and sea surface temperature gradients (Rind, 1988). Attempts to model hydrologic changes within GCMs have also been hampered by parameterization of ground hydrology and coarse spatial resolution (Rind, 1988). Consequently, they are unable to provide much detail on small scale surface hydrology (Gleick, 1987a).

Current GCMs do not permit detailed regional estimates due to limitations in computer time and speed, physical parameterizations, and uncertainties in existing data sets (Schlesinger and Mitchell, 1985). Many environmental changes occur in a non-linear fashion, so errors in the "control" scenario create major difficulties when estimating possible impacts from scenarios of global warming. On the other hand, when normal climatological data from observations are used as input, the Thornthwaite model, combined with lake evaporation models and estimates of consumptive use, can replicate the mean hydrology of large watersheds (e.g. Cohen, 1986). Impacts are then estimated using GCM and other scenario anomalies combined with observed normals.

Potential impacts on water resources planning and management differ from purely hydrological impacts, and so require a different perspective. Beran (1986) points out that while all natural water is of hydrological interest, only water that is capable of exploitation (for shipping, hydropower, irrigation, etc.) is of water resources interest. Given the present limitations of climatic change scenarios, the challenge in utilizing climatic-hydrologic-water resources transfer functions for impacts studies is in identifying the scale problems pertinent to the watershed in question, and then determining procedures to overcome them. In addition, regional variations in physical geography, including climate, may influence the choice and application of hydrologic and impacts models.

Model calibration and validation exercises can be performed using historical climatological data and streamflow (Klemes, 1986; Flaschka et al., 1987). However, given the uncertainties in GCM projections at the regional scale, one cannot "validate" a streamflow projection based on an "unvalidated" scenario of climatic change. So, how does one know when the "right" answer is obtained? One alternative is to perform sensitivity studies using a range of scenarios, to see if the watershed tends to respond in a particular direction. If there is any "robustness" among the various scenarios (e.g. most GCM experiments indicate increased precipitation at high latitudes), sensitivity studies for a particular watershed should mirror this "robustness", in terms of the direction of response. Even for a particular case where this is true, there may be systematic errors common to the formulation of the GCMs which result in the "robustness", and which will therefore still not allow much confidence.

The purpose of this case study of the Saskatchewan River Sub-basin is threefold:

- a) to test the Thornthwaite-based methodology in a region with a climatic and hydrologic regime that differs from previous regional watershed studies;
- b) to provide first-cut estimates of the impacts of global warming scenarios on water resources in the Saskatchewan River Sub-basin; and
- c) to consider implications on future water-related impacts research in the Canadian Prairies.

2 METHODOLOGY AND DATA

2.1 Net Basin Supply at The Pas, Manitoba

Climatic fluctuations can have a significant impact on mean annual streamflow, which is assumed to represent the annual Net Basin Supply (NBS) of a watershed's drainage area at that recording station. Several case studies of other watersheds (Cohen, 1986, 1987b; Singh, 1987) have focussed on estimating the impacts of climatic warming scenarios on NBS. Subsequently, impacts on water users, such as hydroelectric power producers, municipalities and commercial shipping were determined (Sanderson, 1987; Cohen, 1987a; Singh, 1987). The basic objectives are the same in the present case study.

Changes in NBS in the Saskatchewan River Sub-basin could have serious implications, particularly for agriculture. In a study using GCM output, Manabe and Wetherald (1986, 1987) projected possible major declines in soil moisture in the Canadian Prairies, which would be associated with summer warming of up to 9°C. Such a decline could lead to increased consumptive use of water for irrigation, and possibly, decreased NBS. This would have side effects on hydroelectric facilities in the Nelson River Sub-basin downstream.

At this point, it is appropriate to review the methodology for estimating annual NBS from climatological and consumptive use data, and to determine whether it would be necessary to modify the approach, so as to account for differences in prevailing climate and hydrology between this case study area and those examined elsewhere. Annual NBS has been determined in previous studies (e.g. Cohen, 1986, 1987b) as follows:

$$\text{NBS} = R + P_{\text{lake}} - E_o - \text{consumptive use} \pm \text{diversions} \quad (1)$$

where R is overland runoff (mm), P_{lake} is overlake precipitation (mm), and E_o is open water evaporation (mm). These annual values are converted to units of discharge (m^3/s) using

$$\begin{aligned} \text{m}^3/\text{s} = \\ (\text{mm}/\text{a}) * \text{drainage area} (10^6 \text{ m}^2) * (10^{-3} \text{ m}/\text{mm}) * (3.1558 * 10^{-7} \text{ a}/\text{s}) \end{aligned} \quad (2)$$

where "drainage area" in km^2 is converted to m^2 , and a year (a) is assumed to be 365.25 days. In the Great Lakes and James Bay studies, it was assumed that drainage area referred to the total land area in the watershed. That may not be appropriate in this case (see Section 2.3). It was also assumed that long term variations in groundwater would have negligible impact on NBS. There is considerable uncertainty in this assumption, but additional research is needed to determine its validity. For now, this term has been neglected.

SASKATCHEWAN RIVER, THE PAS (mean = 656 m³/sec)

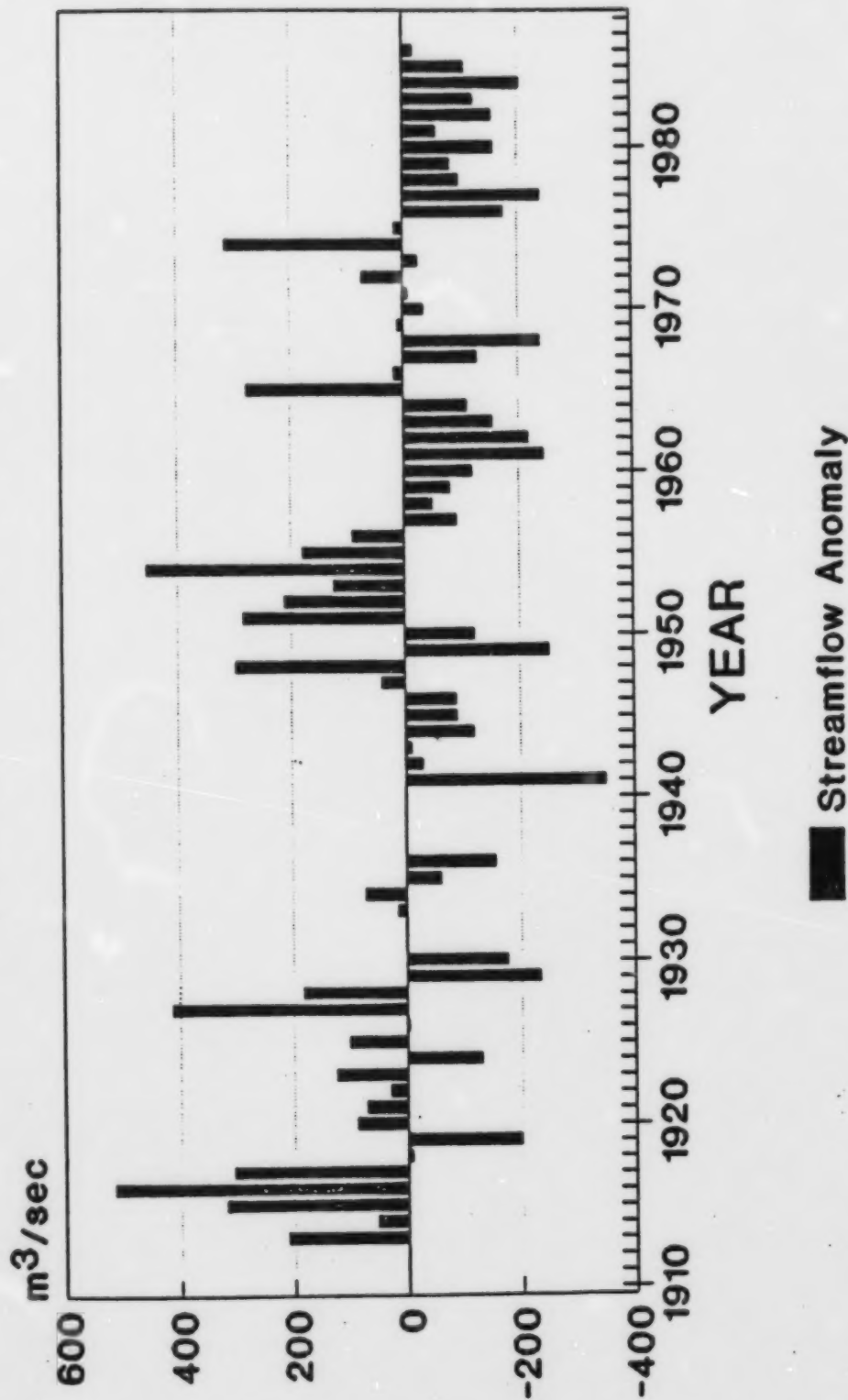


Figure 2--Mean Annual Streamflow at The Pas

Mean annual streamflow anomalies at The Pas, 1913-86. Data are missing for 1931-32 and 1937-40. Source: Environment Canada (1987).

Diversions and consumptive use are traditionally recorded as volume (dam^3) rather than flow. The conversion for annual flow is

$$1.0 \text{ m}^3/\text{s} = 31558 \text{ dam}^3/\text{a} \quad (3)$$

Consumptive use in some localities in the Saskatchewan River Sub-basin includes groundwater as well as surface water. Since groundwater pumpage does not represent water extracted from the stream, this was subtracted from total consumptive use. This term therefore represents consumption of surface water only, which is not returned to the stream, and so is considered a loss in Equation 1.

There are two major diversions of water from the sub-basin, the St. Mary and the Qu'Appelle. These provide water which is mostly used for irrigation in the Milk River area of Montana (USA) and southern Alberta, and in southern Saskatchewan, respectively (PPWB, 1982). Four other major diversions provide transfers within the sub-basin, and so are not included.

The sub-basin has a total drainage area of about $364,000 \text{ km}^2$. This study, however, will focus on streamflow at The Pas, Manitoba, rather than the sub-basin's mouth, since flow data are more reliable there. The actual study area covers about $347,000 \text{ km}^2$, or 95% of the sub-basin. Thus, the lakes on the eastern boundary of the sub-basin (Figure 1, dashed line) are not included. Only 1.5% of the sub-basin is open water, and the exclusion of these lakes reduces the open fraction to about 1%. Lake becomes a very minor component of NBS, and so is incorporated into R in this study. Similarly, E_0 from lakes becomes less important here. However, evaporation from reservoirs is a different matter, particularly since they are located in the warmer sub-arid areas in the southern half of the sub-basin (south and west of Saskatoon). In this study, reservoir evaporation is included in the consumptive use term, since it has been viewed by others in that manner (e.g. PPWB, 1982). Thus, Equation 1 becomes

$$\text{NBS} = \text{R} - \text{E}_0 - \text{consumptive use} - \text{diversions} \quad (4)$$

Annual NBS at The Pas has fluctuated between $307 \text{ m}^3/\text{s}$ in 1941 and $1170 \text{ m}^3/\text{s}$ in 1916 (Figure 2). The 1951-1980 mean is $650 \text{ m}^3/\text{s}$, which is about 1% lower than the mean of $658 \text{ m}^3/\text{s}$ for the length of record covering the 1913-1984 period. The 1951-1980 value is used in this study since it corresponds to the period used to estimate climatic "normals". Figure 2 also shows that in 22 of the last 28 years, recorded flow has been below the 1913-1984 average.

2.2 Scenarios of Climatic Warming

Five scenarios were derived from GCM output and adapted for use in this study. Two of them had previously been adapted for use within the Canadian Climate Program (Hengeveld and Street, 1986--included in this report as Appendix 1) and had been used in a number of Canadian studies (Arthur, 1988; Cohen, 1986, 1987a,b; Sanderson, 1987; Singh, 1987; Smit, 1987; Williams et al., 1987). The other three were based on recently obtained GCM outputs which were utilized in a study of the United States directed by the Environmental Protection Agency (Smith and Tirpak, 1988).

As indicated in Section 1, GCMs do not, as of this time, perfectly simulate the present climate, nor generate detailed estimates of climatic changes. If regional studies are attempted, the difference in scales between global climatic models and regional watersheds must be recognized, and steps taken to overcome it. This involves adapting global climatic model output for regional studies, as well as scaling up from regional impacts to global impacts (Gates, 1985). In the above cases, GCM projected anomalies at the models' grid points were combined with normals from actual station observations. The normals for each grid point were determined from isoline maps based on 1951-1980 data (Hengeveld and Street, 1986).

One scenario originated from 2 x CO₂ (i.e. equivalent doubling of atmospheric CO₂ concentrations) experimental results produced by the Goddard Institute for Space Studies (GISS) GCM (Hansen et al., 1983, 1984). These were originally provided for 8° x 10° grid squares, but were interpolated to points at 4° x 5° intervals (Bach, 1987). The Bach data set, referred to herein as "GISS84" was one of those used in the earlier Canadian case studies. This scenario was also used in a global set of regional studies of impacts on agriculture (Parry et al., 1987). The second 2 x CO₂ scenario was adapted from a 4 x CO₂ experiment using an earlier version of the Geophysical Fluid Dynamics Laboratory (GFDL) GCM (Manabe and Stouffer, 1980). Grid spacing was at 4.5° x 7.5° intervals. This will be referred to as "GFDL80".

The three newer scenarios were: 1) the original 8° x 10° GISS output interpolated by eye ("GISS87") to the same points as in Bach's work, but with contours plotted by the Contour Analysis Software Package produced by the Canadian Climate Centre (Hydro-meteorology Division, 1984); 2) a 2 x CO₂ experiment from a more recent version of the GFDL model (Wetherald and Manabe, 1988) with identical grid spacing to the previous one ("GFDL87"); and 3) a new model produced at Oregon State University ("OSU") by Schlesinger and Zhao (1988) with a 4° x 5° grid spacing identical to GISS84.

It is important to note that GFDL87 is quite different from GFDL80. GFDL87 has been used to estimate possible changes in soil moisture (Manabe and Wetherald, 1986). That experiment indicated decreases in summer soil moisture, associated with pro-

jections of increases in June-August temperatures of as much as 9°C in the North American mid-continent, including the Saskatchewan-Nelson Basin. These soil moisture decreases are not indicated for this basin in GFDL80 (see Manabe et al., 1981).

When utilizing scenarios with different grid point intervals, it is possible that different regional "normals" for NBS would be computed. This was the case in an early Great Lakes study, where there was a difference of 2.5% in the region's "normal" precipitation between the GISS and GFDL networks (Cohen, 1986). If the "normals" are significantly different from each other, it may indicate that the various grid networks are not adequately describing the region's climate. The problem was addressed in the Great Lakes case by applying all percentage change results to the normals from the denser GISS84 network (Cohen, 1987b).

The above problem in the Great Lakes study turned out to be relatively minor, compared with the situation that emerged in the Saskatchewan River Sub-basin. There is a very large gradient in precipitation, with high values at the western edge and much lower ones elsewhere. This is illustrated in Table 1. The GFDL points miss the orographic precipitation that occurs in the Rocky Mountains along the Alberta-British Columbia border. Fortunately, the 4° x 5° grid point at 50°N 115°W is better placed to identify this feature of the region's climate.

In order to assess the representativeness of the two sets of grid points, a preliminary estimate of normal R was attempted using 1951-1980 climatic normals. Methodology is discussed in more detail in Sections 2.3-2.5. Assuming a drainage area of 347,000 km², normal R was estimated to be 828 m³/s and 188 m³/s for the 4° x 5° and GFDL grid point sets, respectively. Given that mean streamflow at The Pas was about 650 m³/s, and that losses due to diversions and consumptive use had not yet been accounted for, it appeared that the 4° x 5° set more adequately described the regional hydroclimate. However, uncertainties regarding snowfall measurement, as well as the representativeness of the 50°N 115°W point for a square that is half prairie, makes it difficult to perform any model validation exercise, i.e. the ability of the methodology to reproduce 1951-1980 mean NBS cannot be proven or disproven. This has implications for future research and monitoring. Appendix 2 discusses the problem of grid point representativeness in more detail.

For the purpose of this study, the 4° x 5° grid point set was chosen for all subsequent calculations. Consequently, it became necessary to interpolate the GFDL projected scenarios onto the 4° x 5° set of grid points. The interpolation of GFDL grid values onto the finer 4° x 5° grid was a relatively simple task because both grids are uniformly spaced. Since it was desirable to have consistent and repeatable interpolations of all the fields, an objective method was used. Barnes (1964) objective analysis (OA) technique was found suitable for this purpose. It

is an interpolation scheme based on the premise that the two dimensional distribution of an atmospheric variable can be represented using harmonic analysis. Similar to other empirical OA techniques, a weighting function is defined and applied to the input field grid values which are within a specified radius of influence from the output field grid point being interpolated.

Table 1. Mean 1951-1980 Precipitation (mm)
at Scenario Grid Points.

Month	1	2	3	4	5	6	7	8	9	10	11	12	Total ¹
4° x 5° grid													
54°N 115°W	25	20	19	21	43	87	87	78	33	16	24	25	476
54°N 110°W	22	17	19	18	40	78	81	65	42	16	15	22	434
54°N 105°W	19	14	22	21	40	72	81	53	51	28	27	25	452
54°N 100°W	19	17	25	24	37	60	71	59	57	34	36	25	464
50°N 115°W	99	54	50	51	50	75	47	56	45	50	51	99	725
50°N 110°W	22	23	16	39	43	63	43	43	36	19	18	25	389
50°N 105°W	19	20	22	30	50	75	50	47	39	19	18	19	405
GFDL													
55.5°N 112.5°W	22	23	16	15	43	87	87	78	51	25	21	25	491
55.5°N 105.0°W	25	23	22	21	31	54	87	62	57	28	33	28	470
55.5°N 97.5°W	22	14	22	33	43	57	81	71	63	47	30	37	520
51.1°N 120.0°W	53	25	25	24	34	51	31	50	27	25	30	50	424
51.1°N 112.5°W	16	17	16	24	37	63	37	53	36	12	15	16	341
51.1°N 105.0°W	19	17	25	24	43	72	56	47	33	22	15	22	394
51.1°N 97.5°W	25	17	31	33	53	75	62	74	51	34	27	22	504

¹ Rows may not add precisely due to rounding.

The application of the Barnes technique required the specification of two parameters--E, which specifies the error resulting from the loss of information when values beyond the radius of influence are not considered, and F, which determines the level of smoothing. For this interpolation, E was set to 5.0, which resulted in less than 1% information loss from values outside the radius of influence, and F was set to 1.0 for minimum smoothing. To avoid boundary problems, a set of GFDL grid values covering at least two grid intervals beyond the 4° x 5° region of interest was used as input for each field being interpolated.

The Barnes interpolation was applied to GFDL80. When GFDL87 became available, it was decided to use the same interpolation procedure as for GISS87. Since both are based on objective con-

tour analysis routines, differences due to interpolation should be unbiased and smaller than real differences in the various scenarios (e.g. see comparison of GISS84 and GISS87 results, next paragraph and Section 3.2).

Precipitation data at 50°N 115°W for the interpolated scenarios are shown in Table 2. These are listed separately because of the importance of this data point in estimating NBS in this study (see Section 2.3). Note the large decreases in the GFDL80 scenario. This is actually the only one of its seven grid points to show a decrease in mean annual precipitation, but because of its importance to R in the Saskatchewan River Sub-basin, this difference will carry through to estimates of NBS (Section 3.2). GFDL87 exhibits a very different picture, somewhat closer to the other scenarios. The GISS84 and GISS87 scenarios are quite similar, except for September, in which the grid point in GISS84 is just west of a negative anomaly centred in southern Saskatchewan.

Table 2. Changes in Monthly Precipitation Projected by Each Scenario for the Grid Point at 50°N 115°W.

Month	1951-1980	GISS84	GISS87	GFDL80	GFDL87	OSU
Jan.	99 mm	39%	32%	-76%	17%	9%
Feb.	54 mm	36%	46%	-65%	-11%	9%
Mar.	50 mm	33%	28%	-65%	15%	16%
Apr.	51 mm	28%	15%	-21%	34%	32%
May	50 mm	24%	22%	6%	13%	4%
June	75 mm	23%	18%	5%	-25%	22%
July	47 mm	18%	18%	-40%	-10%	-10%
Aug.	56 mm	11%	15%	26%	9%	25%
Sept.	45 mm	4%	-25%	-26%	40%	13%
Oct.	50 mm	13%	25%	-68%	3%	-17%
Nov.	51 mm	19%	33%	-56%	-2%	9%
Dec.	99 mm	29%	27%	-76%	2%	5%

TEMPERATURE SCENARIOS

(change from 1951-1980 normal)

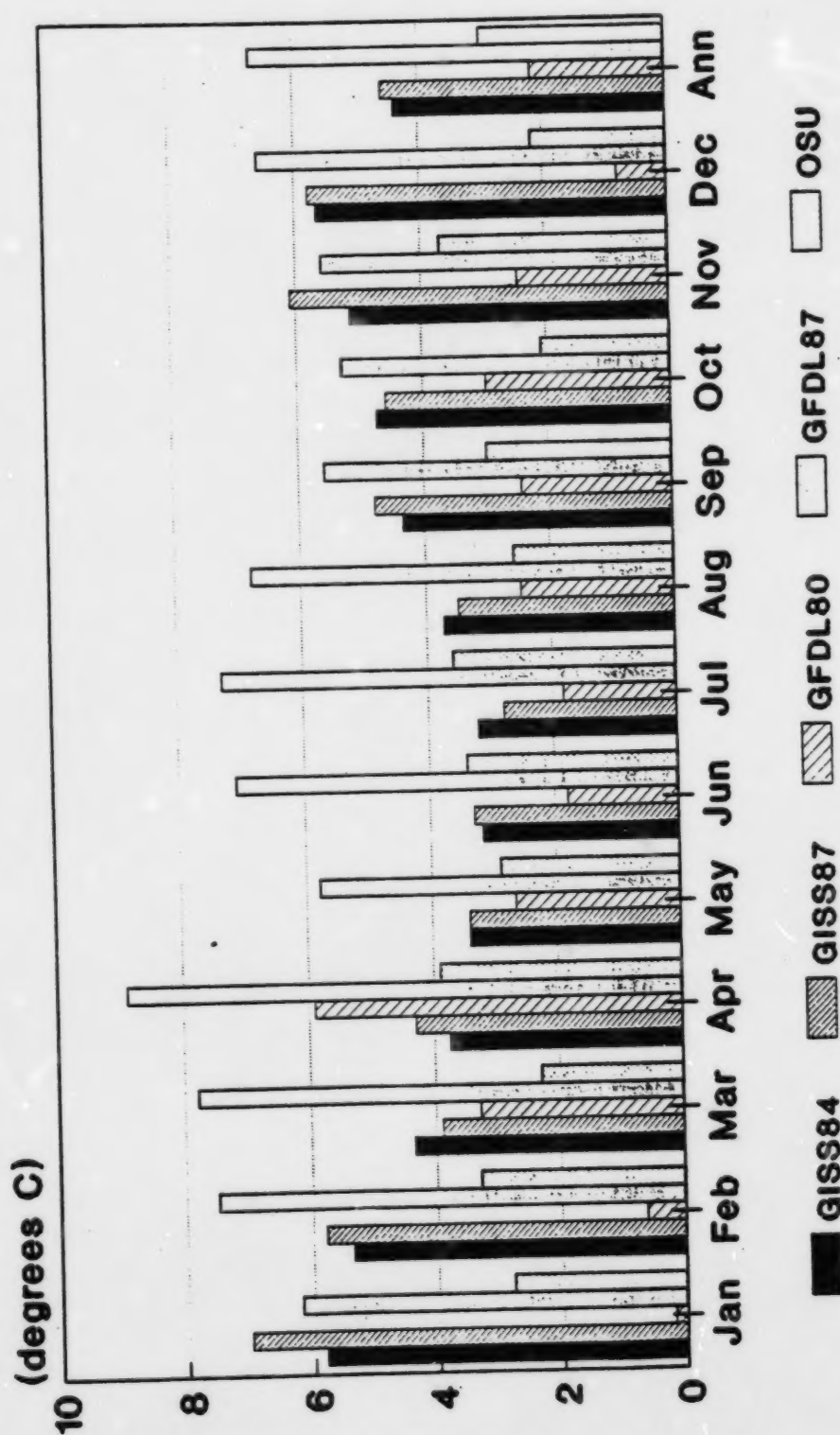


Figure 3--Saskatchewan River Sub-basin Temperature Scenarios

PRECIPITATION SCENARIOS

(change from 1951-1980 normal)

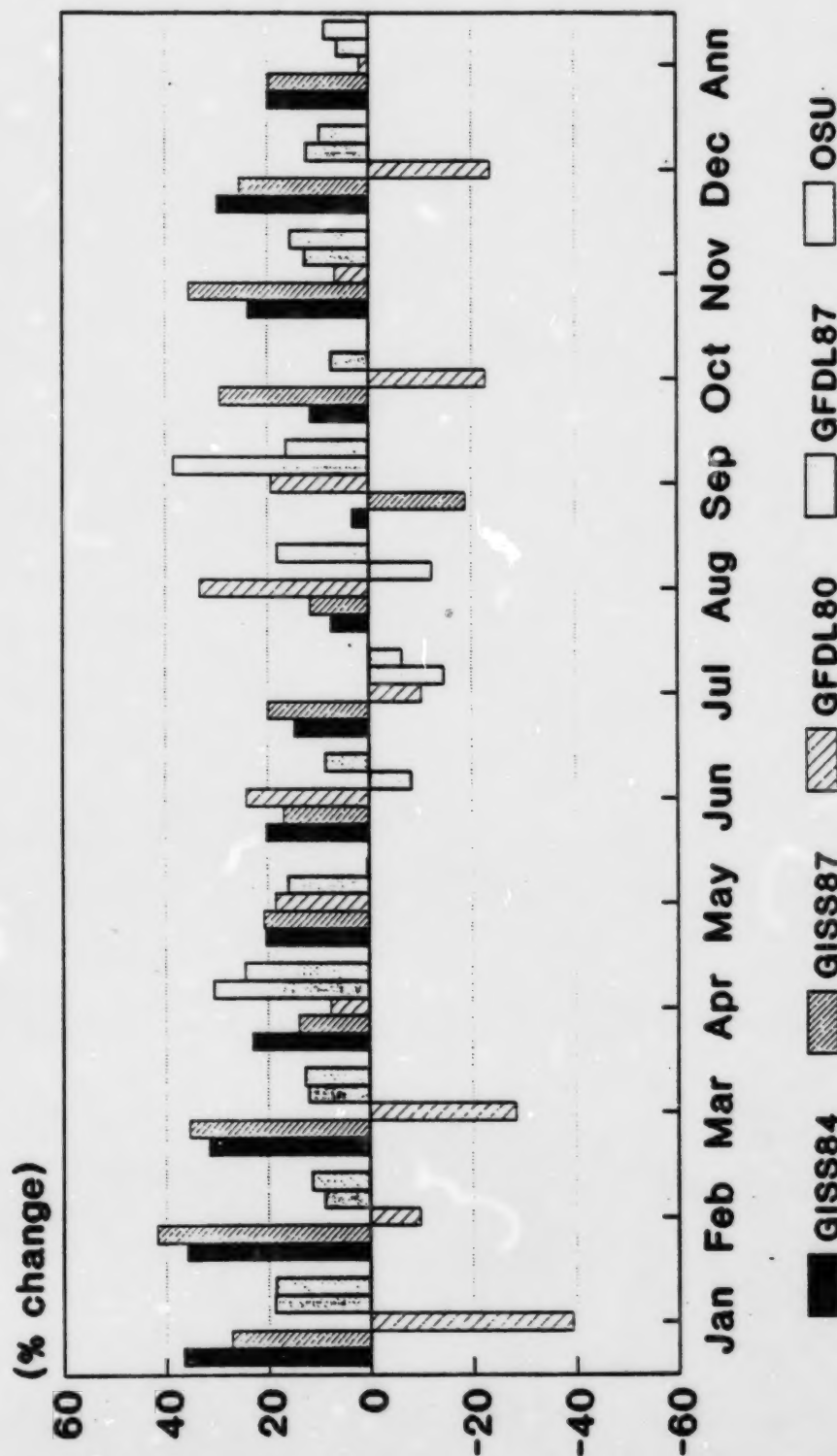


Figure 4--Saskatchewan River Sub-basin Precipitation Scenarios

Although the above interpolation solved one problem, it was felt that the estimated normal R value of $828 \text{ m}^3/\text{s}$ was probably too high, since losses due to diversion and consumptive use were unlikely to account for the entire residual of $178 \text{ m}^3/\text{s}$. Mowchenko and Meid (1983) noted that the contribution of R from much of the basin east of the Rocky Mountains is usually quite low, due to low soil moisture levels and the presence of terminal sub-basins or "dead drainage areas", in which a considerable rise in water level at potential outlets would be required before outflow could reach the Saskatchewan River and other larger sub-basins. It therefore became necessary to make additional modifications to the procedure for estimating R , so as to account for this feature of the region's geography. This is discussed in Section 2.3.

2.3 Runoff

The Thornthwaite climatic water balance (Mather, 1978) estimates R and soil moisture deficit as residuals after accounting for P and potential evapotranspiration, the latter being dependent on temperature and daylength. Actual evapotranspiration is often less than potential, particularly when water supplies (P , soil moisture) are insufficient to meet the needs of vegetation. Despite its empirical nature, the Thornthwaite approach has been found to provide reasonably reliable estimates of water balance components in most climates (Mather, 1978). It is also fairly easy to apply a wide range of climatic scenarios to this model, thereby providing the opportunity to do "comparative hydrology" (Beran, 1986).

It should be noted that the Thornthwaite model does not account for wind effects, or possible changes in transpiration rates that may result from higher CO_2 concentrations (Idso and Brazel, 1984). Consequently, it is assumed that for a given water supply (precipitation and soil moisture), the relationship between transpiration and temperature will not change in a significant way.

For this study, calculations were performed using the Canadian Climate Centre's computer program for monthly data (see Johnstone and Louie, 1984). Soil moisture capacity was assumed to be 100 mm, and the minimum mean monthly temperature required for snowmelt was 0.1°C . For comparative purposes, the water balance model was also run with soil moisture capacity set at 50 mm and 200 mm to see how sensitive the calculations would be to variations in soil depths in the study area.

Regarding the contribution of land areas to sub-basin R , it was noted in Section 2.2 that the assumption of proportional weighting, by the percentage of land area assigned to each grid

point, was probably not valid for this case study. It was therefore necessary to modify the area weights by using ratios of "effective"/"gross" drainage areas. "Gross" refers to total land area which might contribute R under extremely wet conditions. "Effective" (or "dry") represents the area that directly contributes R during a flood with a return period of two years. This area is defined primarily in terms of hydrologic factors rather than topography (Mowchenko and Meid, 1983). The deletion of land that does not contribute to R under "normal" conditions would probably eliminate regions containing shallow depressions or perched ponds, which fill with water during spring runoff. This water would evaporate during summer, and little if any would contribute to streamflow. The use of effective/gross ratios is a way of accounting for this loss. Had we assumed that the ratio was 1.00, NBS would have been overestimated by a considerable amount.

For the complete study area (Figure 1), Mowchenko and Meid (1983) determined an effective drainage area of 223,907 km², for an effective/gross drainage area ratio of 0.64. However, different sections of the sub-basin have different ratios, conceivably ranging from 0.00 to 1.00. Thus, it was necessary to determine this ratio for each data point before R for the entire sub-basin could be calculated (Table 3--see Appendix 3 for a description of the method used to determine the ratios).

Table 3. Effective/Gross Drainage Area Ratios for GISS Grid Points.

Grid Point	Ratio
54°N 115°W	0.78
54°N 110°W	0.31
54°N 105°W	0.72
54°N 100°W	0.79
50°N 115°W	0.73
50°N 110°W	0.33
50°N 105°W	0.24

Applying the ratios from Table 3 new area weights were computed for each of the seven GISS points as follows:

$$\text{weight}_i = \frac{\text{effective area}_i}{\text{total effective area}} \quad (5a)$$

for $i = 1$ to 7, where

$$\text{effective area}_i = \text{ratio}_i \times \text{gross area}_i$$

(5b)

and total effective area is the sum of the effective area for the seven grid points (in this case, 223,700 km² instead of the expected 223,907 km², due to rounding error). These weights are listed in Table 4.

Table 4. New Area Weights for Runoff Calculations.

Grid Point	Gross Area (km ²)	Effective Area (km ²)	Area Weight
54°N 115°W	55900	43600	0.195
54°N 110°W	76100	23600	0.106
54°N 105°W	76500	55100	0.246
54°N 100°W	15700	12400	0.055
50°N 115°W	71500	52200	0.233
50°N 110°W	100500	33200	0.148
50°N 105°W	14800	3600	0.016
Total	411000	223700	0.999

Notes: Gross and effective areas have been rounded to the nearest 100 km².

Gross area includes approximately 52000 km² from dead drainage sub-basins.

The computation of R is shown in Table 5. The sub-basin total is about 693 m³/s. Since losses are not yet included (see Section 2.2), this should compare favourably with the 1951-1980 mean streamflow of 650 m³/s. However, it should be noted that about 75% of sub-basin R comes from the grid point at the Rocky Mountains (50°N 115°W). There are uncertainties in regional estimates of P within this area due to the strong spatial gradient in precipitation and the poor spatial coverage of observing stations (see Appendix 2). The normal P climatology for the Rocky Mountains is uncertain, and this could lead to errors in estimating NBS.

Table 5. Annual Runoff for 1951-1980 Normal Climate.

Grid Point	Area Weight	Runoff (mm)
54°N 115°W	0.195	34
54°N 110°W	0.106	7
54°N 105°W	0.246	40
54°N 100°W	0.055	54
50°N 115°W	0.233	319
50°N 110°W	0.148	24
50°N 105°W	0.016	8
Total	0.999	98.2 mm = 693 m ³ /S

Notes: Values have been rounded.
Area weights obtained from Table 4.

2.4 Consumptive Use of Water

Calculations of the impacts of climatic change scenarios on NBS must include estimates of water consumption which, in populated areas, will be directly and indirectly affected by global warming. Table 6 shows estimates of 1951-1980 mean annual consumptive use for the Saskatchewan River Sub-basin. Note that reservoir evaporation is included in the total of 63 m³/s.

Possible errors in the estimate of "normal" consumptive use include differences in averaging period. For example, in the case of reservoir evaporation, some reservoirs did not operate during the entire 1951-1980 period (e.g. Lake Diefenbaker, south of Saskatoon), so there was no loss to the stream until the facility became operational. To account for a number of years of zero loss, the contribution of such facilities to the 1951-1980 sub-basin "normal" was reduced proportionately. In the case of Lake Diefenbaker, it was reduced by 50% because the reservoir was only in operation for the latter half of the period. However, cumulative evaporation loss for the period may not have been linearly related to the duration of operation, due to climatic variability within the averaging period. (There was no accounting for the one time loss of water from streamflow to the reservoir upon its initial filling.)

Table 6. 1951-1978 Mean Annual Consumptive Use and Reservoir Evaporation.

Use/Loss	m ³ /s	Notes ¹
Agriculture	46	assume 1951-1978 mean sub-basin irrigated area = 250000 ha
Industrial	2	
Municipal	1	accounts for net gain of groundwater pumped to surface
Reservoir Evaporation	14	assume Lake Diefenbaker annual evaporation pro-rated by 50%
Thermal Power	0	.01-.03 during period of record
Total	63	

¹ All values estimated from data obtained from PPWB (1982).

A hypothetical example is shown in Table 7. In case a, normal climate prevailed throughout the period, and the pro-rated evaporation loss was 50% of the 1951-1980 mean, or 125 m³/s. If the climate during the period of operation was conducive to below "normal" evaporation (case b), but it was assumed that this condition prevailed for the entire period (case c), then the above reduction of 50% would have led to a 25 m³/s underestimate of mean annual loss for the 1951-1980 period. The opposite error (case d) would have occurred under conditions of above "normal" evaporation for the period of operation (case e). Which of these cases applies to the Saskatchewan River Sub-basin? Answering this question would require time series data for 1951-1980 from reservoirs in or near the area.

By far the largest consumer of water in this region is agriculture, which accounts for nearly 75% of total consumption. In 1976, about 90% of this was for district or private irrigation, while the remainder was for livestock and domestic uses (PPWB, 1982).

Land area within district irrigation projects has increased from 115,000 ha in 1951 to over 240,000 ha during the 1960s, and 330,000 ha in the 1970s. Private irrigation only extended over about 30,000 ha during the 1950s and 1960s, but by 1976, the total had risen to over 60,000 ha. Water use per hectare has been fairly stable on privately irrigated lands, ranging from 4.0-4.5 dam³/ha throughout the 1970s. However, during the same period, district irrigation rates fluctuated between 2.9-5.8 dam³/ha (PPWB, 1982). Since district irrigation has accounted for over 80% of all sub-basin irrigation during the study period, it is assumed for this case study that district and private irrigation will show similar responses to global warming.

Table 7. Hypothetical Example of Error in Estimating 1951-1980 Mean Reservoir Evaporation (mm) when Facility Operating During 1966-1980.

	1951-1965	1966-1980 (Operation)	1951-1980 (Mean)	1951-1980 (50% Operation)
a.	250	250	250	125
b.	300	200	250	125
c.	(200)	200	200	100
d.	(300)	300	300	150
e.	200	300	250	125

NOTE: Values in () represent assumed values, based on evaporation during period of operation (see Section 2.4).

Previous work in the Great Lakes region has shown that there is a significant correlation between climatic water deficit (DEF) and monthly municipal water use during summer (Cohen, 1987a). Explained variance (r^2) ranged from 0.25 to 0.55 for most cities. However, because municipal response appeared to be influenced by temperature as well as precipitation (Cohen, 1987a), it was felt that for monthly data, temperature weighted deficit might produce a higher r^2 . Unfortunately, only annual irrigation data could be obtained for the Saskatchewan River Sub-basin. Nevertheless, an attempt was made to produce similar linear models of annual irrigation demand as functions of annual unweighted and temperature weighted deficits. Potential evapotranspiration was applied as the weighting factor (PEWTDEF) as follows:

$$PEWTDEF_{1-n} = \frac{PE_{1-n}}{\text{mean PE}} \times DEF_{1-n} \quad (6)$$

A third model was also tested, using PE as the independent variable, to compare a temperature-only model to the above "moisture availability" models. If water users were responding to moisture availability, the DEF and PEWTDEF models should show higher r^2 than the PE model.

Data for 1955-1983 from the Eastern Irrigation District (EID) southeast of Calgary were used. This is one of the largest districts in the sub-basin, accounting for more than 20% of sub-basin irrigated lands. Climatic data were obtained for Brooks AHRC, Alberta (50°33'N, 111°51'W), located within the District. Results of the linear regression and correlation analyses are shown in Table 8. The three linear models exhibited significant correlations, with the PEWTDEF model performing slightly better than DEF, and considerably better than PE. A scatterplot of the PEWTDEF model is shown in Figure 5. The data point at 395 mm shows irrigation during the 1961 drought, which was the only year to exceed 8 dam³/ha of irrigation at EID. The PEWTDEF model was used to estimate Saskatchewan River Sub-basin agricultural water use for the global warming scenarios.

Table 8. Climatic/Irrigation Models for Eastern Irrigation District, Using Climatic Data from Brooks, Alberta.

A. IRRIGATION = 0.011 (DEF) + 3.25

$$r = 0.70 \quad r^2 = 0.49 \quad \text{SIG} = 0.01 \quad \text{SE} = 0.76$$

B. IRRIGATION = 0.011 (PEWTDEF) + 3.28

$$r = 0.72 \quad r^2 = 0.52 \quad \text{SIG} = 0.01 \quad \text{SE} = 0.73$$

C. IRRIGATION = 0.038 (PE) - 14.60

$$r = 0.55 \quad r^2 = 0.31 \quad \text{SIG} = 0.01 \quad \text{SE} = 0.88$$

Notes: Irrigation expressed as dam³/ha.
 DEF, PEWTDEF, PE are in mm;
 DEF, PEWTDEF expressed as positive values.
 Sample size = 29.
 SIG = level of significance.
 SE = standard error.

When estimating changes in consumptive use due to climatic warming scenarios, it is necessary to consider scenarios of growth of irrigated land area, reservoir facilities, etc. For this study, low and high irrigation scenarios were derived. "Low" assumed that 300,000 ha would be irrigated, or

about 20% less than 1976 district and private irrigation, but 20% higher than the assumed 1951-1980 mean. A similar low scenario is already taking place in some of the High Plains states of the United States (e.g. Texas) due to diminishing water supplies (Postel, 1985). "High" assumed expansion of activity to 500,000 ha, an increase of 100% from the 1951-1980 mean. Thus, a total of ten scenarios were analyzed, two for each GCM-based warming scenario.

Diversions to other watersheds were assumed to remain at present levels. In addition, reservoir evaporation and other losses/uses (except irrigation) were assumed to remain unchanged, though any future increases in reservoir storage and/or population could make evaporation loss and/or other uses become more significant factors influencing NBS.

ANNUAL IRRIGATION VS PEWTDIF (Eastern Irrigation District)

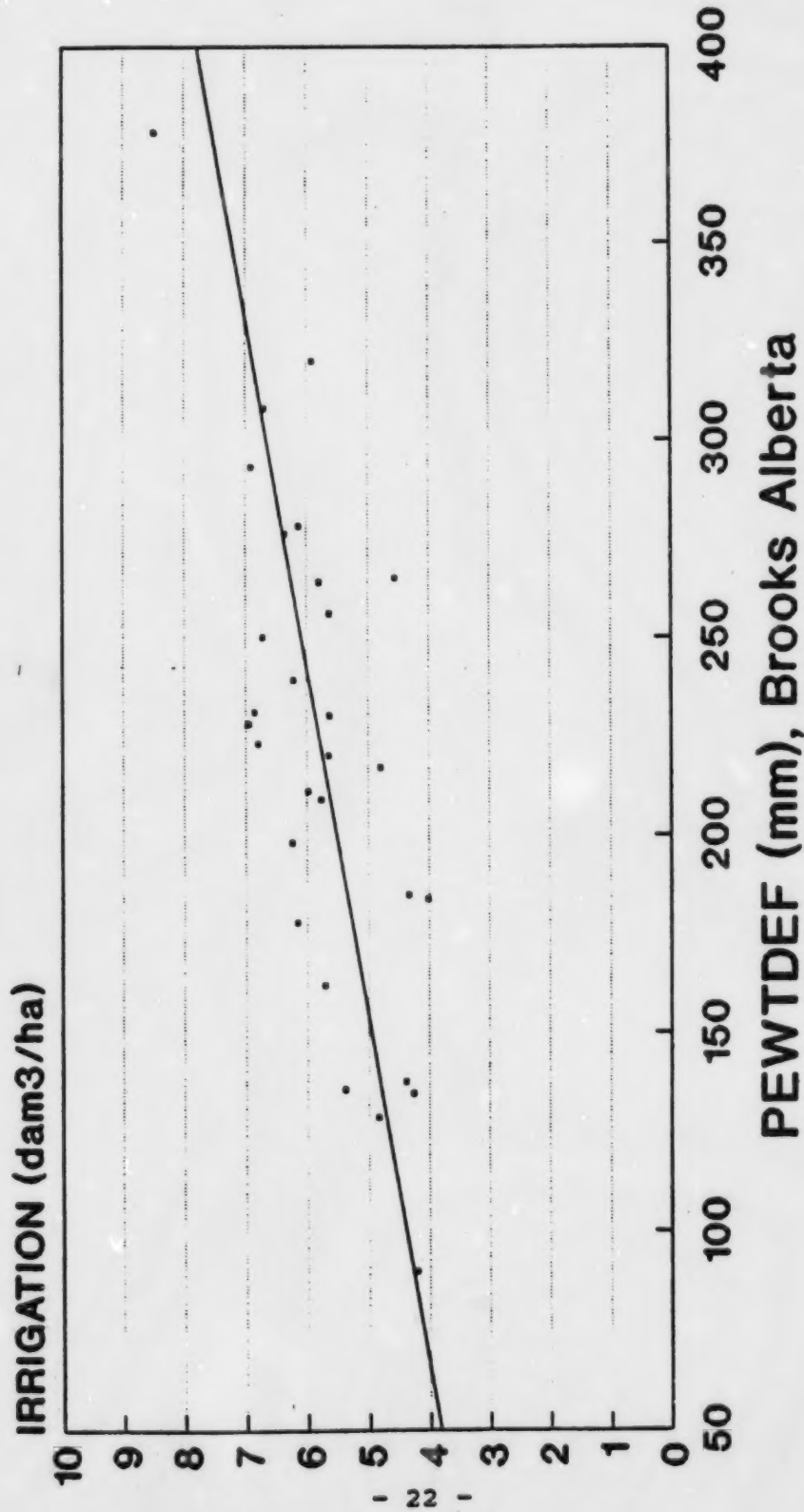


Figure 5. Annual Irrigation at Eastern Irrigation District versus annual PEWTDIF at Brooks, Alberta, 1955-83. See Table 6. Irrigation data obtained from Prairie Provinces Water Board, Regina. Climatic data obtained from archives at the Canadian Climate Centre, Downsview.

3 RESULTS

3.1 Control Run Using 1951-1980 Data

As indicated in Section 2.3, R was estimated to be $693 \text{ m}^3/\text{s}$. This estimate was obtained from the weighted sum of R at the seven grid points (Table 5). In Section 2.4, consumptive use, including reservoir evaporation, was estimated to be $63 \text{ m}^3/\text{s}$ (Table 6). Export of water via diversions is about $215,000 \text{ dam}^3/\text{a}$ (PPWB, 1982), or about $7 \text{ m}^3/\text{s}$. Assuming that Elake is negligible,

$$\text{normal NBS} = 693 - 63 - 7 = 623 \text{ m}^3/\text{s}$$

or about 4% below 1951-1980 mean annual streamflow observed at The Pas. This compares favourably with the 1% error determined in the Great Lakes study (Cohen, 1986), and is considerably better than the errors obtained for the sub-basins within the James Bay region (Singh, 1987). However, as previously noted, uncertainties in runoff estimates at the Rockies preclude any definitive conclusions regarding validation of the water balance methodology.

The above calculation was done using an assumed soil moisture capacity of 100 mm, as in previous water balance studies of this region (e.g. Laycock, 1967). The following estimates for mean annual R were obtained for other assumed capacities:

- a) 50 mm, all grid points..... $928 \text{ m}^3/\text{s}$
- b) 50 mm at 54°N and Rockies, 200 mm elsewhere..... $852 \text{ m}^3/\text{s}$
- c) 100 mm at 54°N , 50 mm at Rockies, 200 mm elsewhere..... $762 \text{ m}^3/\text{s}$
- d) 200 mm, all grid points..... $513 \text{ m}^3/\text{s}$

Higher assumed capacities result in reduced R since larger soil moisture deficits are possible, which would have to be replenished before runoff could occur. The opposite would happen with lower assumed capacities. Compared with observed annual streamflow, case "c" comes closest to matching the 100 mm assumption. If a future detailed assessment of precipitation at $50^\circ\text{N } 115^\circ\text{W}$ indicates that the areal normal is actually lower, cases "b" or "c" may actually provide better estimates. For now, 100 mm will be used in all subsequent scenario calculations.

Another useful validation exercise would have been to compare annual estimates of NBS to annual streamflow for each year during the 1951-1980 period (similar to Flaschka et al., 1987). This would have pointed out how well the Thornthwaite approach performs during extreme years. Unfortunately, this would have required generation of a time series of temperature and precipitation data for each grid point, a somewhat lengthy endeavour. Time series data for actual stations are available, but new effective/gross drainage area ratios would be needed for each station, thereby making it difficult to compare these results

with those generated by the grid point set. Thus, we are left only with the comparison of 1951-1980 normals.

3.2 Estimates from Scenarios

Calculations of annual NBS were performed for the ten scenarios. Results for R in the GISS and GFDL scenarios were considerably different from present normals (Figure 6, Table 9). The GISS scenarios resulted in higher sub-basin R, primarily due to the increases at the grid point within the Rocky Mountains (50°N 115°W). This increase originated from higher snowmelt (Figure 7), which more than offset the warmer temperatures and lower soil moisture levels (Figure 8).

Table 9. Annual Sub-basin Runoff for 1951-1980 and Scenario Climates.

Grid Point	Area Weight	1951-1980 (mm)	GISS84 (mm)	GISS87 (mm)	GFDL80 (mm)	GFDL87 (mm)
54°N 115°W	0.195	34	61	56	48	28
54°N 110°W	0.106	7	24	22	41	0
54°N 105°W	0.246	40	48	46	74	6
54°N 100°W	0.055	54	68	79	161	39
50°N 115°W	0.233	319	429	422	0	301
50°N 110°W	0.148	24	38	31	0	0
50°N 105°W	0.016	8	21	10	14	9
Total	0.999	98.2	135.9	102.8	41.0	57.4
	m ³ /s	= 693	959	932	289	560

Note: Columns do not total precisely due to round-off errors.

The GFDL80 scenario showed much lower R due to the 41% decrease in mean annual P at the same grid point in the Rocky Mountains. When combined with a projected warming of 3.7°C, mean annual R was projected to disappear from this grid point. This would more than offset increased R and snowmelt from all grid points at 54°N. If this scenario was to become a reality in the twenty-first century, the viability of the Bow and Oldman Rivers as permanent streams would be in doubt. Meanwhile, GFDL87 showed only a slight decrease in R at the Rocky Mountains, but substantial decreases elsewhere, resulting in a decrease in NBS of 20%. OSU showed only a small increase in NBS as gains in the southwest and northeast cancelled out losses at other points.

Projected changes in irrigation are shown in Table 10. Irrigation under GISS and GFDL87 would increase considerably over the 1951-1980 base case climate, since PEWTDEF would be higher. OSU exhibited a moderate increase. A small increase would occur in GFDL80, as the increase in land area would overshadow the effect of lower PEWTDEF.

Table 10. Projections of PEWTDEF and Changes in Irrigation Consumptive Use from 1955-1983 Period for Saskatchewan River Sub-basin.

Scenario	1951-80	GISS84	GISS87	GFDL80	GFDL87	OSU
PEWTDEF (mm)	182	306	307	157	489	252
IRRIGATION (m ³ /s)						
Low	+4 (+9%)	+17 (+37%)	+18 (+39%)	+2 (+4%)	+37 (+80%)	+12 (+26%)
High	+38 (+83%)	+59 (+128%)	+60 (+130%)	+33 (+72%)	+92 (+200%)	+51 (+111%)

Notes: Irrigation obtained from PEWTDEF model in Table 8. Model parameters derived using 1955-83 data.
Mean irrigated area for 1955-83 assumed to be 250000 ha. LOW = 300000 ha. HIGH = 500000 ha.
Mean annual 1955-83 PEWTDEF = 226 mm.
Assume mean annual 1955-83 irrigation = 46 m³/s, based on mean annual rate at Eastern Irrigation District.

The above results were combined with estimates of other consumptive uses and diversions to produce estimates of annual sub-basin NBS (Table 11). Increased irrigation demand occurred in both low and high scenarios due to the increased irrigated land area, and in the GISS, GFDL87 and OSU scenarios, increased summer soil moisture deficits. The increase did not alter the sign of the result for the GISS and GFDL scenarios. GISS continued to show increased NBS, while GFDL exhibited the opposite condition. High irrigation does lead to a change of sign in the OSU scenario, but neither case appears to be very different from present conditions.

CHANGE IN ANNUAL RUNOFF

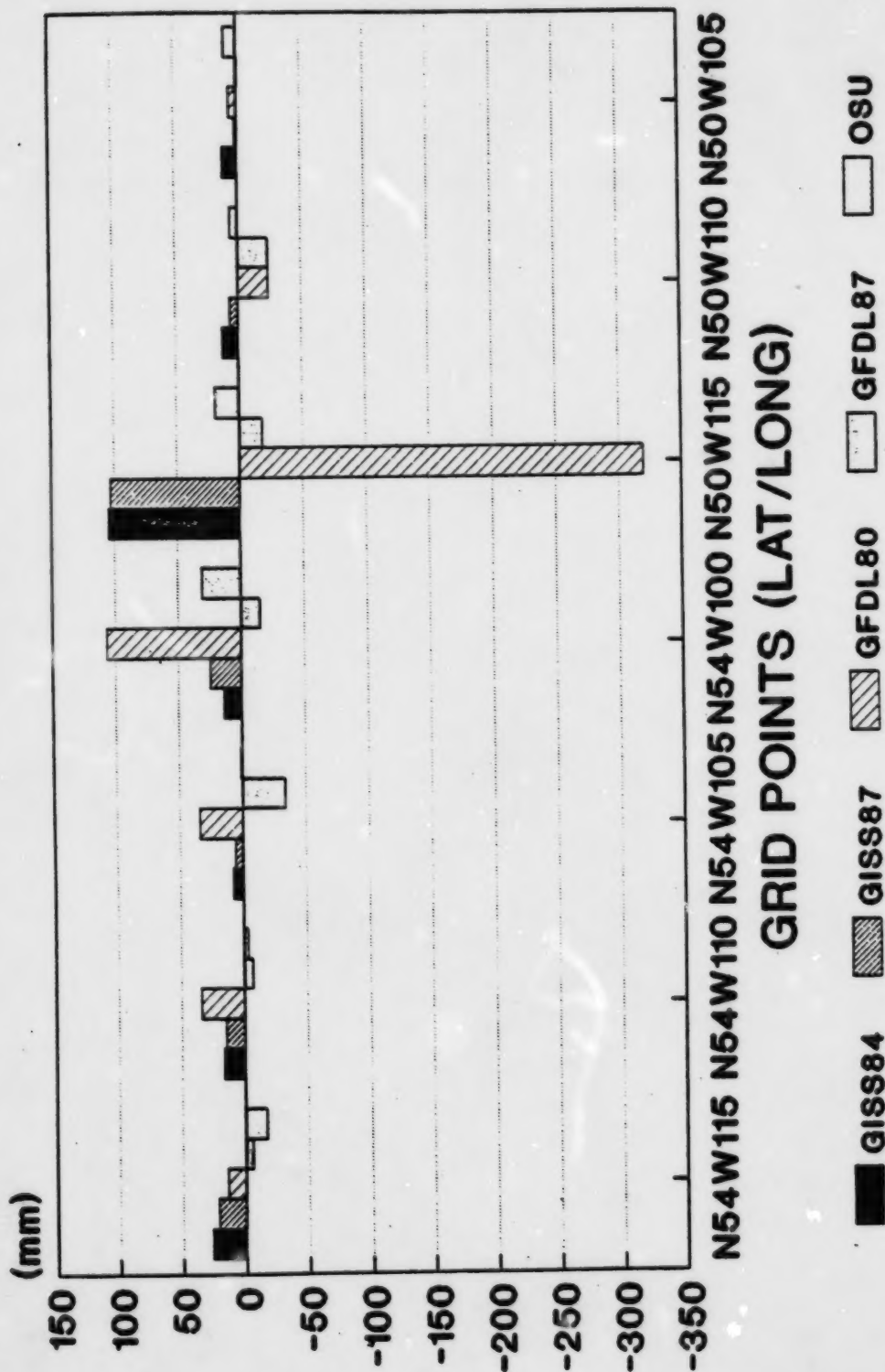


Figure 6. Projected changes in mean annual runoff for scenarios in the Saskatchewan River Sub-basin.

CHANGE IN SNOWMELT

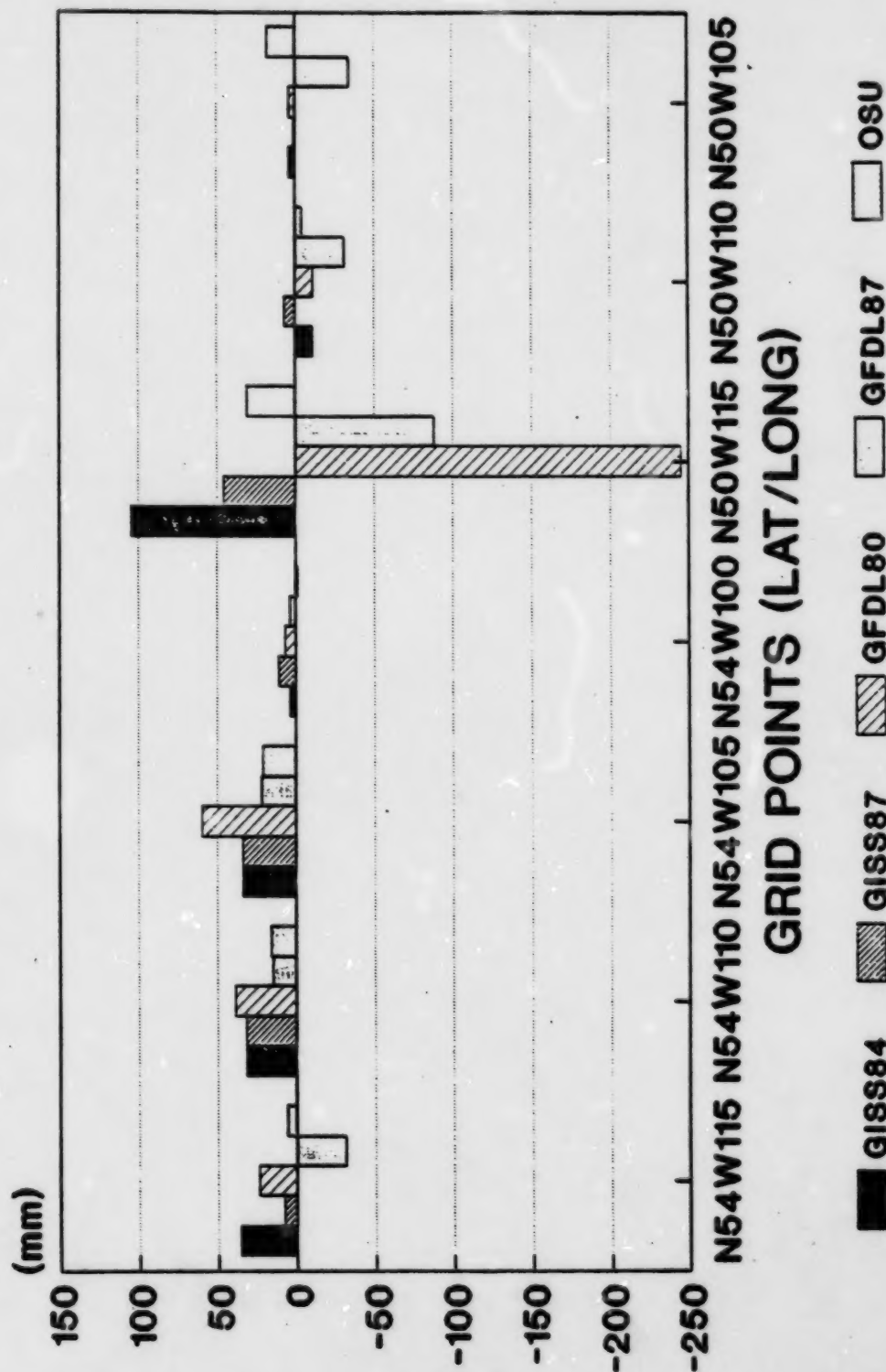


Figure 7. Projected changes in mean annual snowmelt for scenarios in the Saskatchewan River Sub-basin.

CHANGE IN SUMMER SOIL MOISTURE

(obtained from deficit calculations)

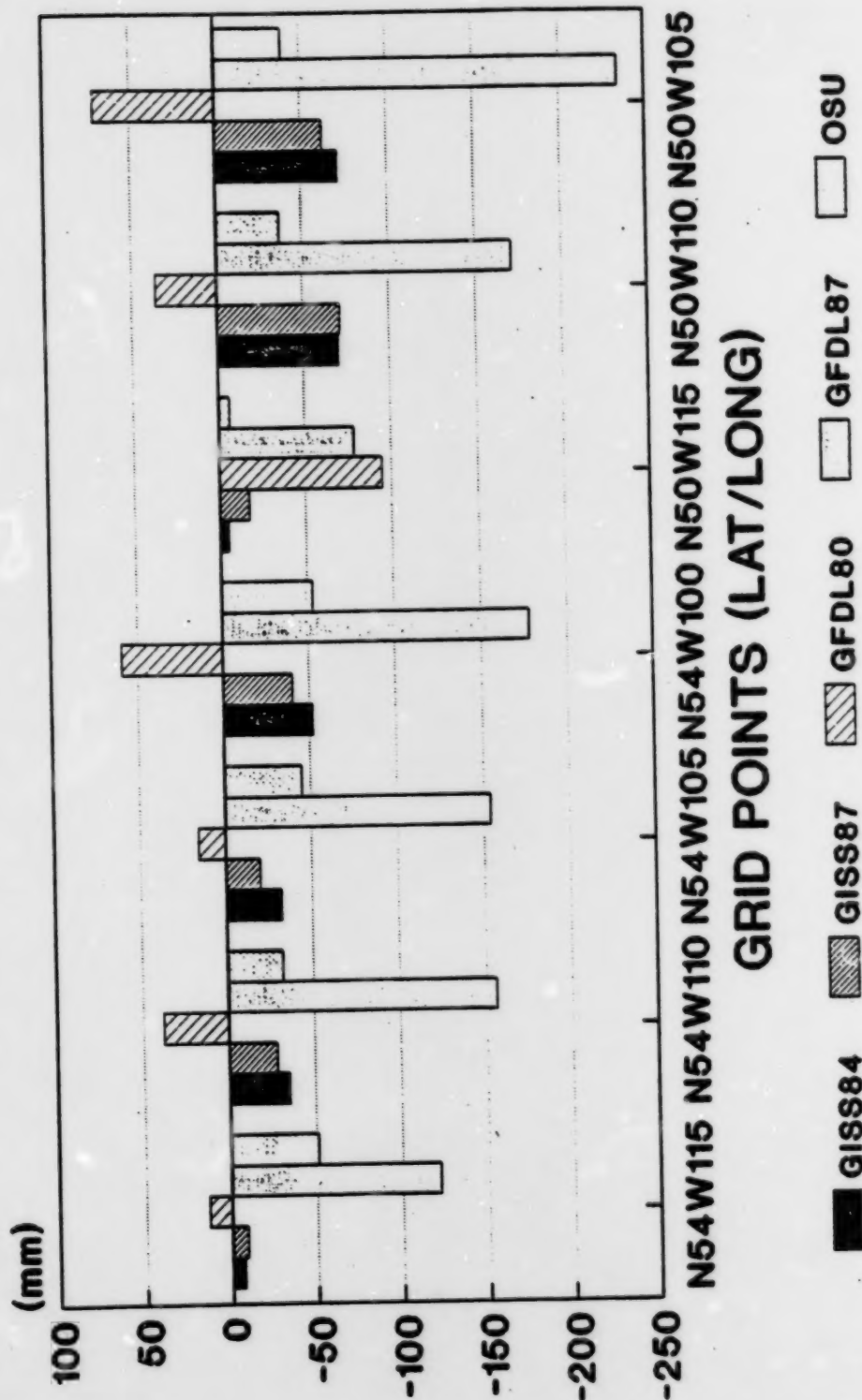


Figure 8. Projected changes in summer soil moisture for scenarios in the Saskatchewan River Sub-basin.

Table 11. Projected Net Basin Supply With Consumptive Use
(m³/s).

	Runoff - Cons. Use - Diversion =			NBS	%Change
"Normal"	693	63	7	623	--
The Pas (1951-80)	-	-	-	650	(+ 4.2)
GISS84-LOW	959	80	7	872	+40.0
GISS84-HIGH	959	122	7	830	+33.2
GISS87-LOW	932	81	7	844	+35.5
GISS87-HIGH	932	123	7	802	+28.7
GFDL80-LOW	289	65	7	217	-65.2
GFDL80-HIGH	289	96	7	186	-70.1
GFDL87-LOW	560	100	7	453	-27.3
GFDL87-HIGH	560	155	7	398	-36.1
OSU-LOW	720	75	7	638	+ 2.4
OSU-HIGH	720	114	7	599	- 3.9

Notes: Consumptive use includes reservoir evaporation.

"Normal": climate = 1951-1980

consumptive use = 1951-1978

Low = 300000 ha irrigated lands.

High = 500000 ha irrigated lands.

These results also demonstrate how seasonal changes in the hydrologic cycle have manifested themselves on annual NBS. The GISS scenarios produce a wetter winter with a higher snowmelt peak and a more arid summer, so GISS84 and GISS87 show higher R and greater consumptive use than GFDL80. Winter is relatively wet in the GFDL80 scenario as well, except in the Rocky Mountains at 50°N 115°W, while summer soil moisture deficits are less severe (i.e. soil moisture levels are higher), indicating a more humid summer. The latter partially ameliorates the warmer temperatures and associated per hectare water requirements, but the loss of Rocky Mountain snowmelt creates a streamflow regime that has a lower (and probably shorter) snowmelt peak, and lower streamflow throughout the year. GFDL87 is generally drier in all seasons because its temperatures are the highest of all scenarios in this study. Consequently, GFDL87 shows lower R and greater consumptive use than the GISS scenarios. Regarding OSU,

the seasonal changes are similar to GISS, but in this case, increased R appears to cancel out the increases in summer consumptive use.

The impacts of the GISS and GFDL scenarios on the hydrology of the Saskatchewan River Sub-basin are fairly large in magnitude. Changes in a variety of hydrologic variables, including the timing, location, duration and extent of runoff, and soil moisture are likely outcomes of scenarios of climatic warming (Gleick, 1987a), and that certainly seems to be the case here. The fact that there is no consensus on the direction of projected changes in NBS is indicative of the uncertainty of GCM projections of precipitation, rather than the water balance methodology employed in this case study.

4 DISCUSSION

4.1 Possible Impacts on Water Resource Users

Water in the Saskatchewan-Nelson Basin is utilized for agriculture, hydro-electric power production, cooling at thermal power plants, recreation and industrial processing. Agriculture is a major consumer of water, in which return flows are considerably less than withdrawals from surface supplies. Certain others, such as hydro-electric production and recreation, are in-stream users that do not "consume" water, i.e. their use of water does not result in a "loss" from surface supplies.

If the status quo is to be maintained, the above results indicate that for the GISS scenarios, an increase in agricultural demand for water would not significantly affect the availability of water for other users, since NBS would be relatively high. A "business as usual" response would probably be sufficient for the OSU scenario as well. Regarding the GFDL scenarios, the low NBS would seriously compromise all users. In fact, the estimated NBS for GFDL80 is lower than any recorded since 1913 (see Figure 2). Such an unprecedented situation would necessitate a major policy response, such as the establishment of a regional water allocation scheme for the sub-basin, involving government agencies, user groups and the public. Should there be increases in population, reservoir storage, industrial or agricultural development, such a scheme might not be required for the GISS or OSU scenarios, but any increases in water demand would only make the situation more critical in the GFDL scenarios.

The level of uncertainty in these results is high, thereby presenting water resources managers with an unclear picture of the future. In addition, the range of scenarios used in this case study do not necessarily indicate the range of error. Nevertheless, the sensitivity of the Saskatchewan River Sub-basin to climate warming scenarios is evident, and it would be prudent to consider long term management alternatives that would reduce the vulnerability of the sub-basin to climatic warming. A number of research initiatives may also be appropriate, and these are discussed below.

4.2 Future Research Needs

Any study of regional climatic impacts encounters the mismatch of scales problem. The application of global climatic scenarios to regional studies continues to be hampered by the need to spatially interpolate data. When this is done for precipitation, particularly in complex terrain, the errors could be very large. Unfortunately, there is no way to "verify" GCM projections, interpolated or not. Comparisons of GCMs (e.g. Schlesinger and Mitchell, 1985) provide important information, but consistency of results among several GCMs for a particular location is still not verification. Nevertheless, GCM-based

scenarios are extremely useful for case studies, such as the Saskatchewan River Sub-basin. Although considerable work remains, it is beyond the scope of this paper to discuss research needs in GCM development. Instead, we shall concentrate on a number of other important problems: data gaps, hydrologic modelling, water use modelling and policy options.

One of the most basic problems in climatology is mapping the spatial distribution of precipitation in complex terrain. The precipitation climatology of the Rocky Mountains is strongly influenced by the topography, so a very dense monitoring network is needed in order to improve the existing data base, and to provide guidance for spatial interpolation of scenario data.

The Thornthwaite climatic water balance model can be used to estimate streamflow on a monthly basis (e.g. Gleick, 1987). However, in a watershed such as this one, where the main source of supply is snowmelt, information about the snowpack is vital. Since the snowpack probably includes older snow deposited in other years, precipitation data alone would probably not be sufficient to model daily streamflow. More work in snowmelt modelling is needed, and in the absence of a good physical model, Thornthwaite or other empirical approaches will be the ones most likely to be applied to this problem.

An additional constraint to the Thornthwaite approach is that the direct effects of elevated CO_2 concentrations on plant water use cannot be accounted for (see Section 2.3). The significance of this is uncertain at this time, but eventually, there will be a need to adjust the model to account for changes in plant water use efficiency. This adjustment will be dictated by plant species and assumed CO_2 concentration.

Water consumption by agriculture is important in this watershed, but the data base is uneven. Annual data from the Eastern Irrigation District were used in this study. Monthly data were more difficult to obtain. Data from smaller irrigation districts were available for only a short period. Regular (monthly) monitoring at irrigation districts throughout western Canada would provide a more detailed data base. Since the correlation between climatic variability and irrigation demand appears to be fairly strong, a better data base on irrigation would allow impacts researchers an opportunity to improve estimates of water resources impacts. This data base should include information on irrigated area and soil type, as well as changes in crop type and water prices, so that non-climatic factors could be accounted for. A similar recommendation had been made by PPWB (1982) for the Saskatchewan-Nelson Basin. Efforts by PPWB to maintain an updated and centralized data base (PPWB, 1982) should be supported.

A similar time series data base should also be established for reservoir evaporation. This would help to overcome the problem discussed in Section 2.4 regarding the pro-rated contribution of reservoirs to sub-basin evaporation loss during the 1951-1980 period.

Finally, it is important to note that the worldwide debate about anthropogenic climatic warming is beginning to reach the public policy arena. A number of symposia and conferences have taken place involving politicians, as well as scientists and policy advisers from many countries and international organizations (e.g. Titus, 1986). The Government of Canada organized such a conference, "The Changing Atmosphere: Implications for Global Security" which was held in Toronto in June, 1988. The kinds of policy questions that are being asked include options for prevention, anticipation, mitigation, and adaptation. Prevention of global warming would largely involve global pollution reduction. Anticipation generally consists of research and monitoring programs at global and regional scales. Mitigation and adaptation strategies also include a regional/local element. Examples might include water allocation schemes, changes in crop scheduling, development of drought resistant crops and changes in water prices and hydro-electricity exports. Which options would be the most appropriate for the Saskatchewan River Sub-basin under various scenarios of global warming? Here is a tremendous challenge for researchers with expertise in policy analysis.

5 EPILOGUE

Differences between the various scenarios of future climate are responsible for some of the uncertainty that prevails in any attempt to study the regional impacts of climatic change. However, there are other sources of uncertainty due to incomplete knowledge of how the natural environment, the economy, and society in general interact with prevailing climate, and how these sectors would adapt to climatic change. The climatic change issue has forced researchers from many disciplines to reconsider the role of climate and climatic information in their work. This fundamental shift in our view of the linkages between climate and the physical and human environments is still in its early stage."

A framework for a complete impacts study of a major watershed, such as the Saskatchewan River Sub-basin, would show many interconnections between climate, hydrology, water resources and various sectors of the regional economy (e.g. Cohen, 1986). It is important that these interconnections be kept in mind when establishing the scope of an impacts study. Is the objective to examine the hydrology of the basin, or is it a broader water resources study? The Saskatchewan River case study is an example of the latter, in that it is oriented towards exploitable water. A number of hydrologic issues, such as changes in timing of peak runoff, have not been considered in detail. However, Gleick (1987b) has used the Thornthwaite approach to address these issues in a basin in California, so it seems reasonable to propose that similar studies using Thornthwaite could be done for basins in western Canada. There are a wide range of other models that could be utilized, but a recent review has indicated that there are few cases available (Beran, 1986).

For many years, the primary focus of climatic impacts research had been on plants, while the hydrologic cycle was only of secondary interest (Falkenmark, 1987). A number of water related studies are beginning to appear in the impacts literature, but there is still a long way to go (Klemes, 1985; Beran, 1986; Askew, 1987; Gleick, 1987a; Lewis, 1989). More research would improve methodology and data availability, and more case studies would provide a clearer picture of the sensitivities of various watersheds to global warming scenarios. The methodology described herein can be used to provide "good" first-cut estimates at the regional scale, although it is obvious that a great deal of research into basic physical/hydrological processes and climatic/water-use relationships is required before more definitive impacts studies could be pursued. It is hoped that the results of this preliminary study of the Saskatchewan River Sub-basin will act as a catalyst for a broader long term effort to investigate potential impacts of projected climate warming on hydrology and water resources in western Canada.

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APPENDIX 1

Development of CO₂ Climate Change Scenarios for Canadian Regions

by

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and

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(1986)

This report was written in 1986 to help document the climatic change scenarios which were distributed by the Canadian Climate Centre to climatic change impacts researchers. It is included as an appendix here because it is not readily available elsewhere.

Please note that the statement on information availability on page A1-5 is out-of-date and that requests for further information about the scenarios should instead be directed to Henry G. Hengeveld at (416) 739-4323.

DEVELOPMENT OF
CO2 CLIMATE CHANGE SCENARIOS FOR CANADIAN REGIONS

H.G. Hengeveld and R.B. Street

1. INTRODUCTION

In recent years the international scientific community has focussed increasing attention on the possible impacts of man on global climate. Climate model experiments suggest that a doubling of atmospheric CO2 concentration, which could occur within the next century, is likely to mean global warming of 1.5°- 4.5°C. Concurrent buildup of other radiatively active trace gases in the atmosphere is likely to amplify this warming. Such a large warming, if it occurs, could exceed anything experienced by the earth's climate during the past several 100,000 years and would undoubtedly have major implications for the socio-economic well-being of our global society. Canada, lying along the cold margins of habitable earth, could become one of the most significantly affected nations of the world.

A number of studies into the implication for Canadians of a doubled CO2 (2XCO2) type of global warming have already been initiated. The number and variety of such studies will undoubtedly increase as interest in this concern escalates. In order to assess the results of such studies on a comparable basis, it is desirable that they be based on common climate change scenarios using a consistent set of assumptions on the manner in which climate may change. Unfortunately, the results of climate model experiments remain as yet uncertain, particularly with respect to precipitation, and are macroscale in detail. Hence these results cannot be used as definitive predictions of future regional climates. On the other hand, the alternative approach of using fixed quantum step changes in temperature and precipitation for impact studies ignores the important seasonal variability of such changes and results in a proliferation in the number of scenarios required.

In response to the above needs and cautions, the Canadian Climate Centre has developed two "what if" scenarios for use in Canadian climate change impact studies by modifying and adapting the results of two general circulation model (GCM) experiments for elevated atmospheric CO₂ concentrations. These experiments were originally undertaken by the Geophysical Fluid Dynamics Laboratory (GFDL) and the Goddard Institute for Space Studies (GISS). While these scenarios are not to be considered as predictions of future climate and consequent effects they do provide plausible estimates of future 2xCO₂ temperature patterns. Precipitation patterns are much more uncertain. However, the scenarios can be very useful as tools in assessing the sensitivity of Canadian socio-economic activities to climate change through case studies.

2. SCENARIO CHARACTERISTICS

2.1 Scenario A (2xCO₂): The original GCM experiment used as a basis for development of scenario A was run for 1xCO₂ and 4xCO₂ concentrations in the atmosphere. Climate variables in this model are tabulated over a worldwide network of 1920 grid points. Canadian regions are represented by a subset of 165 of these grid points at spacings of approximately 4.4° latitude (from 37.8°N to 82.1°N) and 7.5° longitude (from 150°W to 45°W). The experiment output thus provides monthly estimates of the possible macroscale change in a variety of climate variables for a four-fold increase in atmospheric CO₂. To approximate possible effects of doubling CO₂ for use in scenario A, the above 4xCO₂ outputs were divided by two. Modellers suggest that such an approximation may be reasonable for parameters such as temperature. However, the same may not true for precipitation, since changes in this parameter relate primarily to changes in atmospheric circulation patterns. These in turn, could be significantly different for doubled and quadrupled CO₂ atmospheres. Yet, since precipitation outputs of GCM experiments are in general considered uncertain, it is unlikely that the above approximation is less or more realistic for case study

applications than results of a 2xCO₂ experiment or that of any other approaches available today. In all cases precipitation changes for both Scenarios A and B, must be used with considerable caution.

2.2 Scenario B (2xCO₂): GCM experiment results used for Scenario B were originally obtained from model runs at 1xCO₂ and 2xCO₂ concentrations in the atmosphere, with a coarse data grid network spacing of 8 latitude by 10 longitude. These results were subsequently interpolated to a grid spacing of 4° lat x 5° long. The grid network over Canadian territories extends from 38°N to 70°N and 145°W to 50°W. The experiment outputs include monthly mean temperature and precipitation values at each grid point for the two different CO₂ concentrations.

3. OUTPUTS FOR SCENARIOS A AND B

Monthly temperature and precipitation data sets have been prepared for both scenarios in tabular and map formats (see Figures 1-2 and Tables 1-3). Each data set includes the appropriate grid point values for: 1) net change or effect due to doubling of atmospheric CO₂ as derived from the modified GCM experiment results; 2) the 1951-1980 Canadian normals for these grid points; and 3) the addition of 1) and 2) to provide final 2xCO₂ scenarios. Each of these are discussed in greater detail below.

3.1 The effect of 2xCO₂:

For temperature the effect of 2xCO₂ was obtained for each scenario grid point by subtracting the model output for 1xCO₂ from that for the elevated level of CO₂. In the case of the scenario A grid values, these values obtained by subtraction (4xCO₂-1xCO₂) were divided by two to give the effect for 2xCO₂. For scenario B, grid point values were determined by subtracting 1xCO₂ model run values from those of the 2xCO₂ model run.

For precipitation, the effect of 2xCO2 was obtained for each grid point by determining the ratio of the model output for the elevated level of CO2 to the model output for 1xCO2. These grid point values were then expressed as a percentage. For scenario B, the ratio was calculated by dividing 2xCO2 grid point values by those of 1xCO2. In the case of scenario A, the method of calculating the effect of elevated CO2 was:

$$(((4xCO2-1xCO2)/2.0)+1xCO2)/1xCO2$$

also expressed as a percentage. This method allowed a 50% reduction of the effects of a 4xCO2 increase.

3.2 Normals:

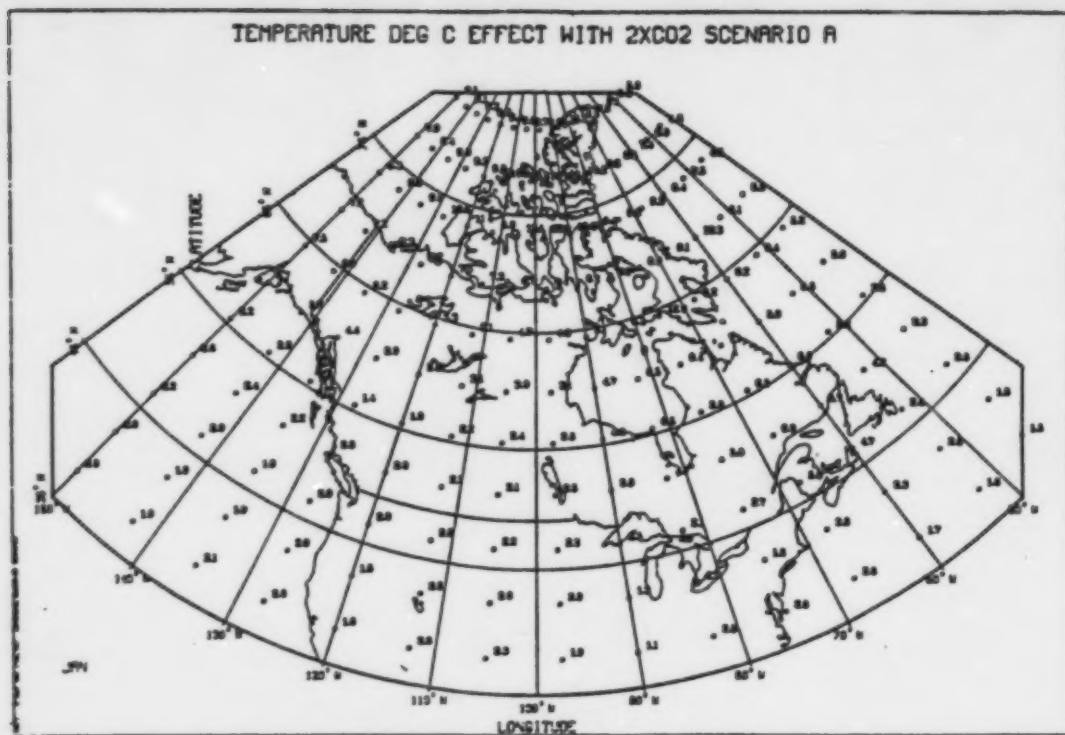
For both temperature and precipitation the normals (1951-1980) extracted from the respective 30 year normal maps for each point on the two grid systems (scenario A and scenario B) were tabulated for each month (see example in Table 2). In the case of grid points located over ocean areas, 1xCO2 values from the respective scenarios were used as estimates of the ocean grid point normals. Values for grid points located in the USA were obtained from 1931-60 American 30 year normal maps. This combination of climate normals and model 1xCO2 outputs was used to obtain the best estimate of the "now" climate.

3.3 The climate with 2xCO2:

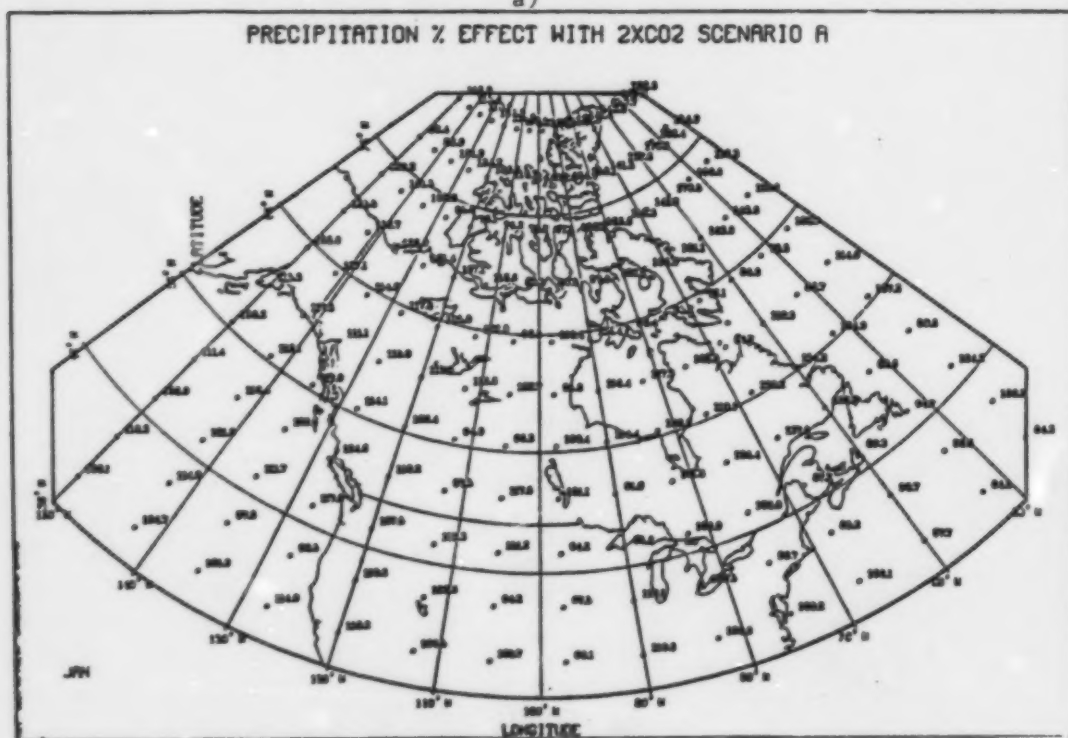
For both temperature and precipitation the effects as determined in 3.1 above have been applied to the normals as described in 3.2 above. The resulting grid point values simulate the impact of the proposed climate change models' outputs for 2xCO2. The resultant maps and respective tables (see example in Figure 3 and Table 3) describe two new sets of possible normal monthly temperature and precipitation values for a doubled CO2 atmosphere, as projected by the two climate change models.

4.0 Availability of Data:

Complete sets of the climate change scenarios described above are available from the Canadian Climate Centre. Requests for further information about the scenarios should be directed to Roger B. Street of the Centre at (416) 667-4627.



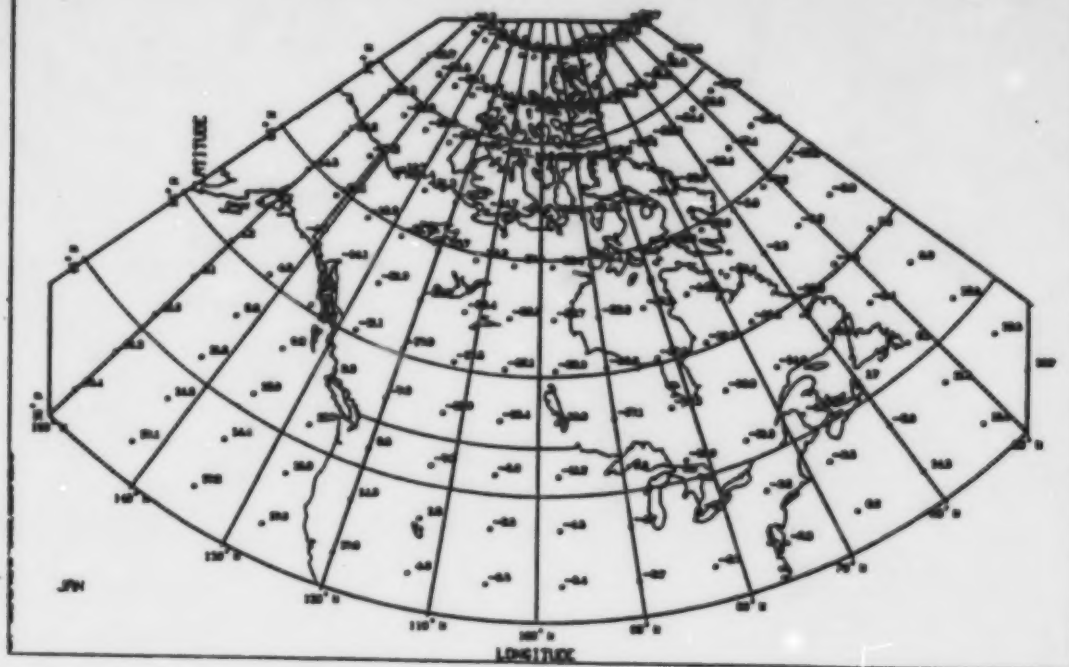
a)



b)

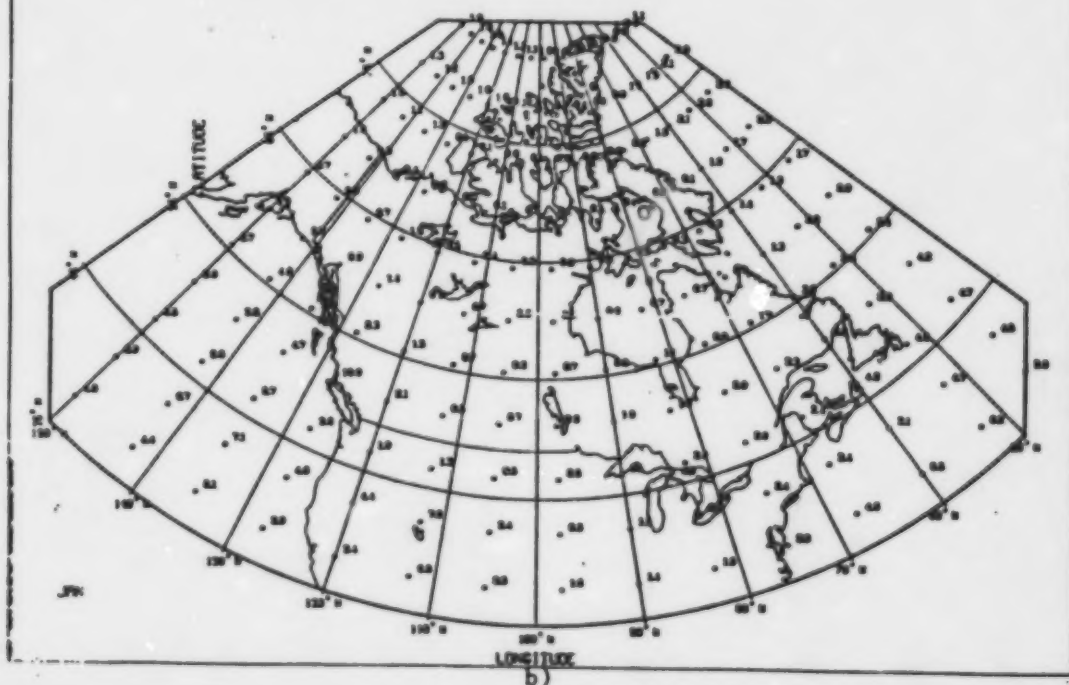
Figure 1. Projected effect of doubling CO_2 on January climate (as tabulated in Table I), presented in map format: a) temperature change; b) precipitation change

TEMPERATURE DEG C WITH 2XCO₂ SCENARIO A



a)

PRECIPITATION MM/DAY WITH 2XCO₂ SCENARIO A



b)

Figure 2. Projected future climate with 2xCO₂ (Table III) presented in map format: a) Temperature; b) precipitation.

TEMPERATURE (DEG C) EFFECT WITH 2XCO₂, MONTH : JAN

SCENARIO A

LATITUDE	LONGITUDE															
	130.0	142.5	155.0	167.5	180.0	192.5	205.0	217.5	230.0	242.5	255.0	267.5	280.0	292.5	305.0	317.5
82.1	9.1	9.1	9.2	9.3	9.4	9.6	9.7	9.8	9.4	9.1	8.5	7.8	7.1	6.3	5.6	
77.7	7.9	8.4	9.0	9.5	9.8	10.4	10.6	10.7	10.6	10.2	9.3	8.5	7.4	6.0	4.8	
73.3	6.3	6.6	6.8	10.5	11.4	8.9	12.1	12.0	12.5	9.4	9.6	9.3	8.4	7.5	4.5	
68.8	7.2	7.2	7.3	7.2	7.5	7.3	8.9	8.4	8.7	7.6	6.9	9.1	12.3	8.1	5.8	
64.4	7.5	8.9	8.2	5.3	5.3	5.1	4.7	4.3	5.1	6.5	12.9	8.2	9.2	9.4	5.2	
59.9	5.7	5.7	4.4	2.9	2.6	3.1	3.0	3.1	4.7	6.5	9.4	7.1	5.9	5.6	5.6	
55.5	3.2	2.9	2.8	1.4	1.5	2.2	2.4	2.6	4.6	6.5	3.8	6.5	6.0	5.2	3.6	
51.1	2.6	2.4	2.2	2.0	2.0	2.1	2.1	2.5	3.9	4.7	5.0	6.0	5.7	4.2	3.3	
46.6	2.2	2.0	1.9	2.0	2.0	2.2	2.2	2.3	2.5	2.1	2.7	5.0	4.7	2.6	2.6	
42.2	2.0	1.9	1.9	2.0	1.8	2.0	2.0	2.0	1.3	1.1	1.8	3.8	3.3	2.0	1.8	
37.8	2.0	1.9	2.1	2.0	1.6	2.0	2.2	1.9	1.1	2.0	2.8	2.6	1.7	1.0	1.5	

a)

PRECIPITATION (%) EFFECT WITH 2XCO₂, MONTH : JAN

SCENARIO A

LATITUDE	LONGITUDE															
	130.0	142.5	155.0	167.5	180.0	192.5	205.0	217.5	230.0	242.5	255.0	267.5	280.0	292.5	305.0	317.5
82.1	116.0	115.9	116.6	106.3	112.2	118.1	123.4	132.8	139.6	137.5	141.4	140.8	129.7	127.0	123.6	
77.7	92.4	82.9	101.9	124.2	108.6	110.7	114.6	118.0	124.8	130.1	141.3	137.6	170.6	182.4	154.9	
73.3	129.2	101.5	100.3	95.6	76.1	76.2	74.7	91.4	129.3	132.8	116.3	141.8	170.3	160.6	118.3	
68.8	125.5	152.7	126.0	121.4	157.1	118.6	85.1	80.0	97.0	131.4	108.0	101.1	143.0	143.8	115.8	
64.4	108.0	127.1	114.0	117.6	105.0	122.0	98.5	110.4	114.4	96.4	95.2	78.1	86.8	73.3	103.7	
59.9	115.3	117.3	111.1	115.9	115.3	118.6	122.7	95.8	116.4	117.7	105.9	84.7	112.3	86.7	114.0	
55.5	103.2	112.1	117.9	114.1	102.4	94.0	96.2	100.4	114.4	132.9	110.1	133.2	154.2	104.9	107.3	
51.1	111.4	116.4	129.4	124.6	118.2	97.5	117.6	131.1	91.9	101.6	136.4	137.6	123.3	82.6	90.6	
46.6	106.9	121.2	111.7	117.0	127.5	115.3	151.2	94.2	95.6	106.0	103.0	87.2	89.3	94.7	104.2	
42.2	116.3	114.0	97.8	93.5	113.6	123.6	94.2	97.5	119.1	109.5	98.7	85.2	93.7	98.6	100.2	
37.8	100.1	104.7	101.9	114.0	118.2	106.5	105.7	99.1	119.6	100.6	100.2	106.1	97.7	84.8	84.3	

b)

Table 1. Climate change projections for doubled atmospheric CO₂ over Canada for the month of January, based on Scenario A:
 a) temperature change (°C); b) precipitation change (%).

TEMPERATURE (DEG C) NORMALS, MONTH 1 JAN

SCENARIO A

LATITUDE	LONGITUDE																
	130.0	142.5	155.0	167.5	180.0	192.5	205.0	217.5	230.0	242.5	255.0	267.5	280.0	292.5	305.0	317.5	330.0
82.1	-37.3	-37.3	-37.3	-37.6	-37.6	-38.4	-38.8	-39.3	-39.7	-39.8	-39.3	-40.3	-39.7	-39.1	-38.3		
77.7	-33.6	-33.9	-34.0	-34.2	-34.6	-35.3	-36.1	-37.1	-38.0	-38.6	-39.4	-39.4	-38.6	-37.9	-36.8		
73.3	-30.7	-30.3	-29.8	-31.5	-30.5	-32.6	-31.0	-32.6	-31.0	-29.0	-28.0	-26.1	-32.6	-34.3	-32.1		
68.8	-29.9	-25.0	-27.0	-28.5	-29.8	-32.6	-33.5	-34.5	-32.8	-31.0	-27.5	-26.0	-25.7	-25.5	-28.1		
64.4	-22.0	-29.0	-25.0	-27.0	-29.0	-31.0	-32.4	-32.7	-31.5	-27.5	-25.5	-25.2	-19.2	-18.6	-18.4		
59.9	-6.5	-10.0	-18.5	-24.6	-25.5	-28.5	-31.0	-29.8	-27.5	-24.0	-24.0	-20.5	-7.2	-5.8	-5.9		
55.5	1.0	2.0	2.3	-12.5	-18.0	-19.8	-24.5	-25.5	-25.5	-23.5	-23.0	-23.0	-16.0	-14.7	2.0		
51.1	5.4	6.2	7.0	1.0	-9.0	-15.0	-18.5	-20.5	-21.0	-20.5	-21.0	-20.0	-12.5	-12.7	4.7		
46.6	9.4	9.6	10.0	11.6	-1.5	-9.5	-9.0	-13.5	-9.5	-15.0	-14.5	-11.0	-3.0	-2.5	7.8		
42.2	12.3	12.7	12.5	14.0	13.2	-1.8	-11.1	-6.5	-8.0	-4.5	-5.0	-13.6	-7.0	9.8	11.7		
37.8	14.4	15.0	15.1	15.6	15.4	2.0	-3.7	-7.3	-1.8	-2.7	-5.1	-2.4	12.6	14.3	15.2		

a)

PRECIPITATION (MM/DAY) NORMALS, MONTH 1 JAN

SCENARIO A

LATITUDE	LONGITUDE																
	130.0	142.5	155.0	167.5	180.0	192.5	205.0	217.5	230.0	242.5	255.0	267.5	280.0	292.5	305.0	317.5	330.0
82.1	0.4	0.4	0.4	0.3	1.0	0.9	0.8	0.7	0.6	0.1	0.0	0.6	0.6	0.7	0.9		
77.7	1.4	1.5	1.5	0.8	1.0	1.0	0.1	0.1	0.1	0.0	0.6	0.9	1.1	1.1	1.3		
73.3	0.3	0.3	1.5	0.1	0.1	0.1	0.1	0.0	0.1	0.2	0.2	1.1	1.2	1.6	2.2		
68.8	0.3	0.2	0.3	0.3	0.2	0.1	0.1	0.1	0.1	0.3	0.2	0.1	1.1	1.2	1.4		
64.4	0.5	0.5	0.6	0.4	0.5	0.3	0.2	0.2	0.3	0.2	0.3	0.3	1.6	1.6	1.6		
59.9	1.6	4.8	0.8	1.2	0.9	0.8	0.5	0.5	0.5	0.5	0.7	0.8	1.2	3.2	1.7		
55.5	3.4	3.5	3.7	2.0	1.5	0.7	0.8	0.7	0.7	0.8	0.8	1.3	2.4	2.2	2.2		
51.1	3.2	3.3	3.7	6.1	1.7	0.5	0.6	0.8	1.1	1.3	1.5	2.4	2.9	3.5	4.0		
46.6	4.1	4.0	5.1	3.1	0.8	1.1	0.3	0.5	1.0	1.4	2.5	2.7	5.4	4.9	4.5		
42.2	2.0	3.8	7.3	4.4	3.9	0.3	3.0	0.5	1.3	1.4	2.4	4.0	3.3	4.8	4.5		
37.8	4.8	4.2	5.0	3.4	2.4	6.4	3.3	1.0	1.2	1.4	3.3	4.3	5.6	7.3	5.4		

b)

Table 2. Thirty year climate normals adjusted to Scenario A grid points over Canadian regions: a) temperature; b) precipitation.

LATITUDE	LONGITUDE														
	150.0	142.5	135.0	127.5	120.0	112.5	105.0	97.5	90.0	82.5	75.0	67.5	60.0	52.5	45.0
84.1	-26.2	-26.1	-26.1	-26.3	-26.4	-26.8	-29.1	-29.7	-30.3	-26.7	-21.8	-32.4	-32.6	-32.8	-32.7
77.7	-25.7	-25.5	-25.1	-24.7	-24.8	-24.9	-25.4	-26.4	-22.4	-20.8	-20.5	-30.9	-31.2	-31.5	-32.0
73.3	-22.3	-21.3	-20.0	-21.0	-19.1	-23.7	-18.8	-20.6	-18.5	-19.6	-18.4	-26.8	-24.4	-26.8	-27.7
68.8	-22.6	-17.8	-19.7	-21.3	-22.3	-24.7	-26.6	-26.1	-26.1	-23.4	-18.6	-16.9	-13.4	-17.4	-22.4
64.4	-14.5	-22.1	-18.8	-21.7	-23.7	-25.9	-27.7	-28.4	-28.4	-21.0	-12.6	-17.0	-6.0	-7.2	-13.2
54.9	0.2	-4.3	-14.1	-21.9	-22.9	-23.4	-28.0	-26.7	-22.8	-17.5	-14.6	-13.4	-1.3	-0.2	-0.3
55.5	4.2	4.4	5.1	-11.1	-17.0	-17.6	-22.1	-22.9	-20.9	-17.0	-19.2	-16.5	-10.0	-9.5	5.6
51.1	8.1	8.6	9.2	3.0	-7.6	-12.9	-16.4	-18.0	-17.1	-15.8	-16.0	-14.0	-8.8	-8.4	8.0
46.6	11.6	11.6	12.0	13.7	0.5	-7.3	-8.8	-14.2	-7.0	-12.9	-11.6	-6.0	1.7	0.1	10.5
42.2	14.3	14.6	14.4	15.9	14.9	1.6	-8.5	-4.5	-4.7	-3.4	-3.2	-4.8	-3.8	11.8	13.5
37.8	16.4	17.4	17.2	17.6	17.0	4.6	-9.5	-5.4	-0.7	-0.7	-2.3	6.2	14.3	15.9	16.7

a)

LATITUDE	LONGITUDE														
	150.0	142.5	135.0	127.5	120.0	112.5	105.0	97.5	90.0	82.5	75.0	67.5	60.0	52.5	45.0
84.1	1.0	1.0	1.0	1.1	1.1	1.1	1.0	0.9	0.8	0.1	0.1	0.8	0.8	0.9	1.1
77.7	1.3	1.2	1.0	1.0	1.0	1.1	0.1	0.1	0.1	0.1	0.0	1.4	1.9	2.1	2.0
73.3	1.0	1.1	1.5	0.1	0.1	0.6	0.1	0.0	0.2	0.3	0.2	1.5	2.1	2.6	2.6
68.8	1.6	0.3	0.4	0.3	0.3	0.1	0.1	0.1	0.1	0.4	0.2	0.1	1.6	1.7	2.2
64.4	0.7	0.3	0.7	1.0	0.5	0.4	0.2	0.3	0.3	0.2	0.3	0.3	1.4	1.3	1.7
54.9	1.9	5.7	0.9	1.4	0.9	0.7	0.8	0.5	0.6	0.7	0.7	0.7	1.3	2.8	1.9
55.5	3.7	4.0	4.4	2.3	1.5	0.7	0.8	0.7	0.8	1.1	0.9	1.7	3.8	2.3	2.4
51.1	3.8	3.8	4.7	10.0	2.1	0.5	0.7	0.8	1.0	1.3	2.0	3.3	3.6	2.9	4.2
46.6	4.5	5.0	5.7	3.8	1.0	1.3	0.5	0.5	1.5	2.0	2.6	2.4	4.8	4.6	4.7
42.2	5.9	6.7	7.1	4.6	4.4	7.8	3.4	0.5	1.5	2.1	2.4	3.4	3.1	4.7	4.5
37.8	4.6	4.4	5.1	3.9	3.4	6.8	2.5	1.6	1.4	1.5	3.3	4.6	5.5	6.2	5.0

b)

Table 3. Projected 2xCO₂ climate regime over Canada (Scenario A) obtained by applying 2xCO₂ effects (Table I) to Canadian normals (Table II):
a) temperature; b) precipitation.

APPENDIX 2

Grid-square Climatic Normals Evaluation

Appendix 2

Grid-square Climatic Normals Evaluation

Objective of this Task

This task is intended to create an estimate of the normal precipitation in the Saskatchewan River basin inside a GISS grid square to illustrate the magnitude of the error in using the Hengeveld and Street (1986) grid-point normals as areal estimates for the Saskatchewan River basin within GISS grid square centred on 50°N 115°W. The Hengeveld and Street normals are presented in the table entitled "Monthly Normal Precipitation (mm) for Grid Point 50°N 115°W". The eastern slopes of the Rocky Mountains are responsible for three-quarters of the run-off in the Saskatchewan River basin according to the Thornthwaite model applied to the current climate, and therefore this grid-square is the most significant to the reproduction of current streamflow climatology by the model (see Figure 1 in the body of this report).

Monthly Normal Precipitation (mm) for Grid Point 50°N 115°W

												Total
Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
99.2	53.7	49.6	51.0	49.6	75.0	46.5	55.8	45.0	49.6	51.0	99.2	725.2

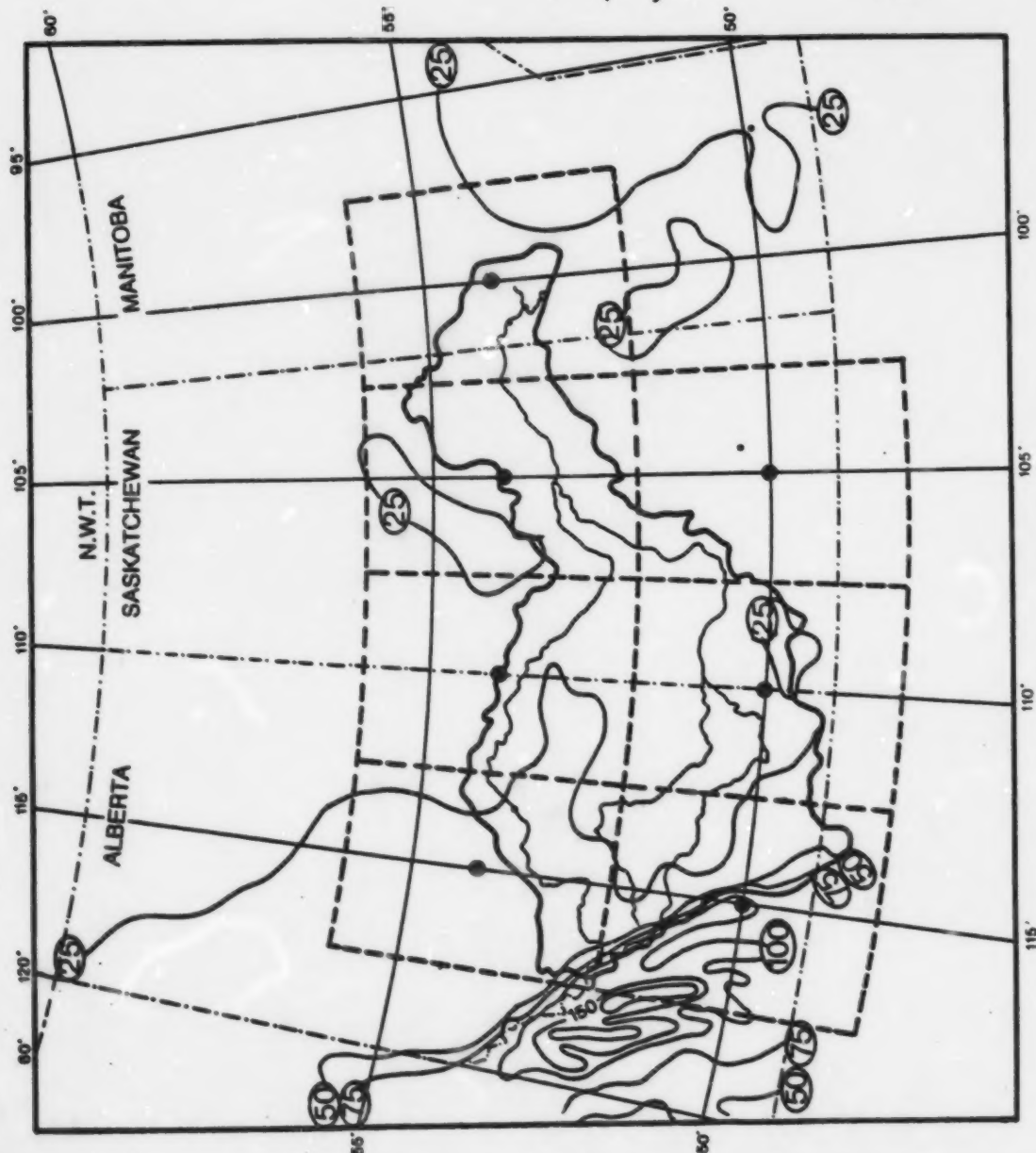
converted from daily gridded normals of Hengeveld and Street (1986)

Map Areal Measurements for the Climatic Normals

The outline of the Saskatchewan River Basin (SRB) (see Figure 1) was enlarged and traced onto photocopies of the original working maps of January and annual normal precipitation published in Climatic Atlas Canada: Map Series 2--Precipitation. Subjective contour analysis of precipitation was performed on the original maps (Sajecki, 1988). These maps have plotted station-normals which are identical to those of the Canadian Climate Normals publications, but, for reason of lack of space for plotting on the map, are incomplete. The maps were photocopied from the original 1:7,500,000 scale maps by P. Sajecki.

The boundaries of the grid square centred on 50°N 115°W were drawn on the photocopied working maps. The result is illustrated in Figure A2-1 (note that Figure A2-1 was not used for planimetry).

Two independent sets of three planimeter measurements of each precipitation zone lying between each pair of contours and simultaneously within both the basin and grid square boundaries, were made. The measurements are presented in the tables entitled "January Normal Precipitation" and "Annual Normal Precipitation".



KEY

- 4°x5° GRID POINT
- - - 4°x5° GRID BOUNDARY
- · - · - PROVINCIAL BOUNDARY
- 25 JANUARY NORMAL PRECIPITATION ISOLINE (mm)
- PROVINCIAL CAPITAL CITY

SCALE: 1:10 000 000 (approx.)

January Normal Precipitation in the GISS Grid Spacing for the
Saskatchewan River Subbasin

FIGURE NO. A2-1

Calculating the Areal Average

The average precipitation for each contour-area was estimated by averaging the bounding contour values, except in the case of the lowest precipitation contour-area where the minimum precipitation value was taken to be the smallest station value in the area. Calculating an average of these contour-area averages, using the contour-areas as weights, is equivalent to a two-dimensional trapezoidal integration. Results are presented in the tables entitled "January Normal Precipitation" and "Annual Normal Precipitation".

January Normal Precipitation

Pcpn. contour area		General	Planimeter		Area	Zone	pcpn. contribution			
> mm	< mm	Description	Trial	Turns	(cm ²)	(mm)	(mm)			
17.9	25	SE Alta.	1	.054	5.4	21.5	115.83			
			2	.055	5.5	21.5	117.98			
			3	.059	5.9	21.5	126.56			
			4	.059	5.9	21.5	126.56			
			5	.052	5.2	21.5	111.54			
			6	.056	5.6	21.5	120.12			
			mean	.056	5.6	21.5	119.76			
			std. dev	.0028	.28	21.5	5.98			
			25	50	S Alta.	1	.059	5.9	37.5	221.25
						2	.055	5.5	37.5	206.25
3	.057	5.7				37.5	213.75			
4	.056	5.6				37.5	210.00			
5	.060	6.0				37.5	225.00			
6	.061	6.1				37.5	228.75			
mean	.058	5.8				37.5	217.50			
std. dev	.0024	.24				37.5	8.87			
50	75	SW Alta.				1	.011	1.1	62.5	68.75
						2	.013	1.3	62.5	81.25
			3	.014	1.4	62.5	87.50			
			4	.013	1.3	62.5	81.25			
			5	.013	1.3	62.5	81.25			
			6	.010	1.0	62.5	62.50			
			mean	.012	1.2	62.5	77.08			
			std. dev	.0015	.15	62.5	9.41			
			75	100	W Alta.	1	.006	.6	87.5	52.50
						2	.005	.5	87.5	43.75
3	.005	.5				87.5	43.75			
4	.002	.2				87.5	17.50			
5	.003	.3				87.5	26.25			
6	.003	.3				87.5	26.25			
mean	.004	.4				87.5	35.00			
std. dev	.0015	.15				87.5	13.56			
sums:						.130	13.0		449.35	

Average pcpn. for basin in grid square: 34.5
standard error: 4.2

Annual Normal Precipitation

Pcpn. contour area		General	Planimeter Area		Zone	Zone pcpn. contribution				
≤ mm	≥ mm	Description	Trial	Turns	(cm ²)	(mm)	(mm)			
372.1	400	SE Alta.	1	.028	2.8	386.1	1080.94			
			2	.030	3.0	386.1	1158.15			
			3	.026	2.6	386.1	1003.73			
			4	.020	2.0	386.1	772.10			
			5	.018	1.8	386.1	694.89			
			6	.018	1.8	386.1	694.89			
			mean	.023	2.3	386.1	900.78			
			std. dev	.0053	.53	386.1	205.25			
			400	500	S Alta.	1	.057	5.7	450	2565.00
						2	.057	5.7	450	2565.00
3	.058	5.8				450	2610.00			
4	.051	5.1				450	2295.00			
5	.053	5.3				450	2385.00			
6	.054	5.4				450	2430.00			
mean	.055	5.5				450	2475.00			
std. dev	.0028	.28				450	124.06			
500	600	SW Alta.				1	.044	4.4	550	2420.00
						2	.040	4.0	550	2200.00
			3	.041	4.1	550	2255.00			
			4	.027	2.7	550	1485.00			
			5	.034	3.4	550	1870.00			
			6	.033	3.3	550	1815.00			
			mean	.037	3.7	550	2007.50			
			std. dev	.0063	.63	550	345.67			
			600	700	W Alta.	1	.029	2.9	650	1885.00
						2	.030	3.0	650	1950.00
3	.032	3.2				650	2080.00			
4	.017	1.7				650	1105.00			
5	.020	2.0				650	1300.00			
6	.017	1.7				650	1105.00			
mean	.024	2.4				650	1570.83			
std. dev	.0069	.69				650	449.24			
						.139	13.9	6954.12		

Average pcpn. for basin in grid square: 500.3
standard error: 99.0

Conclusion and Discussion

The Hengeveld and Street (1986) January grid-point normal for 50°N 115°W is 188% higher than (or 288% of) the corresponding estimated areally representative normal for the basin inside the grid-square, while the annual grid-point value is 45% higher. This demonstrates that the grid-point values are poorly representative of the normals analyses for grid-square area within the Saskatchewan River basin. The annual value itself has not been used in the Thornthwaite modelling procedure; monthly data were

used instead. However, this discrepancy of annual precipitation values is illustrative of the approximate minimum magnitude of the error.

The areal estimates themselves have a systematic high or low error for the area depending on whether or not the analysed field is convex or concave. Examination of Figure A2-1 reveals that most of the precipitation analysis has a concave nature; therefore, the areal estimates are biased high. The lowest precipitation area (e.g. 18-25 mm on the January normal precipitation map) may not be concave, and thus may have a slight low bias on the corresponding areal average. On the other hand, the highest precipitation areas' upper contour bound lies outside of the basin, so the areal precipitation estimate has an additional factor to cause a high bias. Despite the difficulty of quantitative analysis for this component of the error, our judgement is that the net effect is to cause a modest (i.e. less than 20%) high bias in the overall precipitation estimate for the analysed precipitation field in the grid square area in the basin.

A standard error was also calculated for the areal estimates, based solely on the standard deviations of the sets of six planimeter measurements. This standard error represents the major source of random error present in the estimate.

The error in using the normal precipitation map analysis to represent the actual precipitation field, on the other hand, is most certainly a low bias error. This is so because the analysis was done for southwestern Alberta using climatological station normals which do not represent the upper elevations of the basin where the precipitation values are undoubtedly highest. The latter is true because of the strong correlation of precipitation with elevation present even on the eastern (lee) side of the Rocky Mountains (see Table entitled "Stations used in Normal Precipitation map analyses").

The elevations of the stations used in the normals analyses averaged 1096 m (1103 m) for the annual (January) normals map analysis. The highest peak in the Saskatchewan River basin inside this grid-square is Mount Forbes at 3500 m, and a significant portion of the basin inside the grid-square is higher than 1600 m. The highest climatological station used inside the basin was Lake Louise at 1524 m. Even if nearby stations in British Columbia influenced the analysis on the eastern slopes of the Rocky Mountains, few of them are at high elevations either.

This situation is to be expected; a climatologist who performed many of the contour analyses warns that the contours are not intended to be used for point precipitation interpolation estimates, nor are the climatological effects of mountainous areas able to be represented in detail at the scale of the maps (Gullett, 1988). Nor does Hengeveld and Street (1986) claim that the grid-point values are in fact regionally representative.

It is further interesting to note that the contour analysis of normals is not self-consistent, i.e. there is not a water balance between the annual and sum of monthly precipitations. For example, the 50°N 115°W grid-point has a linearly interpolated normal annual precipitation value of about 650 mm, whereas the sum of the monthly normal grid-point values is 725.2 mm. Of course, in such an analysis there is no a priori attempt made to reconcile the separate analyses; it is mainly the consistency of technique used by the analyst which produces such self-consistency as there is.

Stations Used in the Climatic Atlas's Normal Precipitation Mapped Precipitation Contour Analyses

Climatological Station Number	Climatological Station Name	Province	Latitude	Longitude	Elevation (m)	Normal Precipitation	
						Annual (mm)	January (mm)
3031348	CARMANGAY VILLAGE	Alberta	50°08'N	113°07'W	645	446.2	34.4
3022136	DRUMHELLER ANDREW	Alberta	51°28'N	112°52'W	719	372.1	20.0
3026480	THREE HILLS	Alberta	51°39'N	113°18'W	841	391.4	20.3
3026521	TROCHU 2	Alberta	51°50'N	113°13'W	871	408.0	22.7
3035173	PICTURE BUTTE	Alberta	49°53'N	112°47'W	899	<u>412.7</u>	29.1
3032800	GLEICHEN	Alberta	50°52'N	113°03'W	902	387.1	19.0
3020040	ACME CDA EPF	Alberta	51°29'N	113°25'W	905	439.9	28.1
3030300	ARMADA EXP. STA.	Alberta	50°24'N	112°41'W	911	391.2	18.7
3020760	BOWDEN	Alberta	51°59'N	114°01'W	915	499.6	27.6
3033880	LETHBRIDGE A	Alberta	49°38'N	112°48'W	929	422.7	23.6
3022325	ELWORA	Alberta	51°58'N	113°12'W	930	423.1	22.8
3034166	MAJORVILLE	Alberta	50°41'N	112°42'W	930	378.1	17.9
3032685	FORT MACLEOD EXP. ST.	Alberta	49°43'N	113°24'W	953	433.9	24.0
3035420	RAYMOND	Alberta	49°27'N	112°42'W	957	420.3	<u>24.8</u>
3036208	STRATHMORE EAST	Alberta	51°03'N	113°25'W	963	449.6	32.8
3034160	MAGRATH	Alberta	49°25'N	112°52'W	978	<u>999.9</u>	17.6
3032690	FOR MACLEOD STAND OFF.	Alberta	49°32'N	113°20'W	991	<u>475.3</u>	31.7
3024920	OLDS	Alberta	51°47'N	114°06'W	1040	488.4	22.1
3031F5F	CLARESHOLM MEADOW CREEK	Alberta	49°56'N	113°45'W	1052	472.4	24.1
3033138	HERRINGTON EAST	Alberta	50°36'N	113°21'W	1067	403.9	22.7
3031093	CALGARY INT'L A	Alberta	51°06'N	114°01'W	1084	423.8	16.2
3021950	CROSSFIELD	Alberta	51°25'N	114°10'W	1128	501.1	18.1
3033240	HIGH RIVER	Alberta	50°29'N	114°40'W	1219	488.2	22.2
3036640	TURNER VALLEY	Alberta	50°43'N	114°21'W	1237	574.3	21.9
3011663	CLEARWATER RS	Alberta	51°59'N	115°14'W	1280	655.7	26.5
3031676	COCHRANE	Alberta	51°13'N	114°26'W	1280	<u>494.8</u>	27.1
3050600	BEAVER MINES	Alberta	49°28'N	114°10'W	1286	644.7	56.3
3031000	CALDWELL	Alberta	49°09'N	113°38'W	1311	723.1	53.9
3051720	COLDMAN	Alberta	49°38'N	114°35'W	1341	569.0	57.3
3031400	CARWAY	Alberta	49°00'N	113°22'W	1359	515.3	31.9
3053600	KANANASKIS	Alberta	51°02'N	115°03'W	1390	657.4	34.5
3050520	BANFF	Alberta	51°11'N	115°34'W	1397	471.0	38.2
3052270	ELBOW RS	Alberta	50°54'N	114°42'W	1433	610.7	21.8
3052780	GHOST RS	Alberta	51°19'N	114°47'W	1434	<u>553.8</u>	16.6
3055485	RED DEER RS	Alberta	51°40'N	115°13'W	1451	570.0	23.8
3053760	LAKE LOUISE	Alberta	51°25'N	116°10'W	1524	683.9	78.6
1173210	GOLDEN	B.C.	51°18'N	116°58'W	787	477.2	68.8
1150060	ABERFELDIE	B.C.	49°30'N	115°22'W	805	571.1	69.7
1151288	CANAL FLATS RANGER STN.	B.C.	50°09'N	115°49'W	817	369.1	53.3
1177640	SPELLIMACHEEN	B.C.	50°55'N	116°24'W	818	451.6	55.9
1171020	BRISCO	B.C.	50°49'N	116°15'W	823	427.0	49.7
1153282	GRASHERE	B.C.	49°06'N	115°05'W	869	493.7	43.3
1158730	WASA	B.C.	49°49'N	115°38'W	930	403.0	32.8
1152102	CRANBROOK A	B.C.	49°36'N	115°47'W	939	451.2	54.0
1152670	ELKO	B.C.	49°18'N	115°06'W	939	604.5	62.8
1154405	KOOTENAY NAT. PARK RADIUM	B.C.	50°39'N	116°01'W	1088	547.0	59.1
1152899	FORDING RIVER COMINCO	B.C.	50°11'N	114°52'W	1702	725.7	104.1
1155402	NATAL HARNER RIDGE	B.C.	49°46'N	114°50'W	1890	840.8	127.4

notes: 999.9 means missing

underlined values were not plotted on the working maps and hence not used in the normals analysis

Summary of Station Values

		Climatic Atlas's Mapped Analyses' Precipitation Normals	
Area of Interest		Annual	January
Alberta Average (mm):		494.1	28.7
Alberta Standard Deviation (mm):		100.8	13.6
B.C. Average (mm):		530.2	65.1
B.C. Standard Deviation (mm):		101.9	14.1
Alberta Elevation average (m):		1096	1103
B.C. Elevation average (m):		1034	

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APPENDIX 3

Determination of Gross and Effective Drainage Areas in the Saskatchewan River Basin within GISS Grid Squares

Appendix 3
Determination of Gross and Effective Drainage Areas
in the Saskatchewan River Basin
within GISS Grid Squares

Objective of this Task

This task is intended to create estimates of the effective drainage areas for each GISS grid square covering the Saskatchewan River basin, for the current climate. These ratios will be applied to grid square precipitation amounts, both the normals and those derived from GCM 2 x CO₂ scenarios, to enable calculation the portion of the precipitation potentially available for run-off (i.e. precipitation prior to evapotranspiration and consumptive calculations). The effective/gross drainage grid square estimates are based on similar current estimates provided by PRFA for hydrometric stations in the Saskatchewan River basin (PFRA, 1988).

Definitions

Gross Drainage Area

"The gross drainage area of a stream at a specified location is that plane area, enclosed by its drainage divide, which might be expected to entirely contribute runoff to that specified location under extremely wet conditions. The gross drainage boundary is the drainage divide (i.e. the height of land between adjoining watersheds)." (PFRA, 1983, p. 5).

Dead Drainage Basin

"The drainage area contributing to... major depressions (sloughs and/or lakes) from which there is no drainage to the main stream even under extremely wet conditions... is referred to as a dead drainage area and the local watershed tributary to this depression is referred to as a dead drainage basin." (PFRA, 1983, p. 6).

Gross-Gross Drainage Area

This task report refers to the entire area within the outside boundaries of the Saskatchewan River basin as the gross-gross drainage area. The gross-gross drainage area thus includes both the gross drainage areas and the dead drainage areas.

Effective Drainage Area

"The effective or dry drainage area is that portion of a drainage basin which might be expected to entirely contribute runoff to the main stream during a flood with a return period of two years. This area excludes marsh and slough areas and other natural storage areas which would prevent runoff from reaching the main stream in a year of "average" runoff." (PFRA, 1983, p. 5).

"Since the effective drainage area concept implies a natural drainage condition, developments such as dams, diversions and drainage ditches, were, as much as possible, ignored in the delineation of effective drainage areas." (PFRA, 1983, p. 6).

Determination of Drainage Areas in the Saskatchewan River Basin

Determination of Gross-Gross Drainage Area by Grid Square

The gross drainage area of 346976.0 km² for the hydrometric station at The Pas (station number 05KH005) (PFRA, 1988) does not include the dead drainage basins. Consequently, when the area of portion of the Saskatchewan River basin lying within each grid square is determined (see below), it comprises the gross-gross drainage area, i.e. 346976.0 km² plus the area of the dead drainage basins which are shown in Table 1. The figures in Table 1 are from PFRA (1988, p. 17), except for the area of the Middle Lake / Lake Lenore basin. It was determined as a fraction of the Quill Lakes dead drainage basin (listed as 11324 km² by PFRA (1983, p. 4)) by planimetering the areas of basins 5KA (Middle Lake / Lake Lenore) and 5MA (Quill Lakes) on a copy of the Active Hydrometric Station map.

Note that the Middle Lake / Lake Lenore dead drainage basin is explicitly pictured in Energy, Mines and Resources Canada (1985). This map depicts the Middle Lake / Lake Lenore basin as not included in the Saskatchewan River basin, in contrast to the Saskatchewan River basin outline on the Prairie Provinces Hydrometric Station map. The outline on the Prairie Provinces Hydrometric Station map was used throughout this study.

Table 1--Dead Drainage Basins in the Saskatchewan River Basin

Drainage Basin Name	Area (km ²)	Is basin a part of grid square centred on latitude/longitude:							
		50°N 105°W	50°N 110°W	50°N 115°W	54°N 100°W	54°N 105°W	54°N 110°W	54°N 115°W	
Maple Creek	13755	no	yes	no	no	no	no	no	no
Pakowki Lake	5318	no	yes	yes	no	no	no	no	no
Middle Lake / Lake Lenore	3854	no	no	no	no	yes	no	no	no
Sounding/Eyehill Creek	<u>25152</u>	no	yes	no	no	no	yes	no	no
Total Dead Drainage in the Saskatchewan River basin	48079								
Saskatchewan River (Gross at The Pas)	<u>347267.4</u>								
Saskatchewan River (Gross-Gross at The Pas)	395346.4								

Planimetry

The area of the Saskatchewan River basin within each of the seven grid squares was measured and is reported in Table 2.

The areas were measured on the photocopy of the Prairie Provinces Hydrometric Station map, which had a slightly different scale than the original. Thus the areas totalled 410997 km² rather than the correct value for the gross-gross area of 395346 km². The scale difference between the photocopy and the original 1:2,000,000 scale is documented in Table 2. This difference of 2.02% accounts for most of the 15651 km² error between the grid square area and the gross-gross area of the Saskatchewan River basin. The remaining error of 1.8% is readily ascribed to planimetric measurement error.

The approximately correct Saskatchewan River basin area within each grid square can be estimated by normalizing the planimetrically measured areas with respect to the gross-gross drainage area. This requires the reasonable assumption that the measurement errors are uniform over the basin.

Table 2--Planimetric measurements of drainage areas

Areas of SRB in GISS grid squares
latitude longitude area (km²)

50°N	105°W	14802
50°N	110°W	100484
50°N	115°W	71492
54°N	115°W	55903
54°N	110°W	76117
54°N	105°W	76465
54°N	100°W	15714

total:		410977
--------	--	--------

First trial scale =	51.49 km/inch
	165.73 km ² /(0.25 inch) ²
Second trial scale =	165.96 km ² /(0.25 inch) ²
% difference of trials =	-.14%

Scale of photocopied map versus original

linear measurements:

from Alta./B.C./Mont. border to Grand Rapids--	
on photocopy	56.7 cm
original	56.1 cm

from Man./Ont./Minn. border to 54°N 120°W--	
on photocopy	89.9 cm
original	88.9 cm

Average linear scale of photocopied map to original:
101.1%

Average areal scale of photocopied map to original:
102.2%

Determination of Effective/Gross-Gross Drainage Area Ratios
for Each Grid Square

The effective drainage areas within each grid square could not be determined directly since precise boundaries of dead drainage basins and the effective drainage areas were not available from the Prairie Provinces Active Hydrometric Station map and PFRA (1986). Such a determination should be possible if the detailed 1:250,000 scale overlay maps of effective drainage areas described by PFRA (1983) were used. These were not immediately available when this task was performed.

Instead, it was possible to estimate the effective / gross-gross drainage ratios for each grid square as follows. PFRA (1986) lists the effective and gross drainage areas for each hydrometric station. Hydrometric stations were chosen on or near

the upstream and downstream borders of each grid square. The upstream effective [gross] drainage areas (if any) were then subtracted from the downstream effective [gross] drainage areas to obtain the effective [gross] drainage area for each grid square (see Table 3).

The stations used are indicated on Figure A3-1, along with their gross drainage areas and the approximate delineation of the dead drainage basins. Figure A3-1 also shows the dead drainage basin areas (very approximately), the boundaries of the upstream and downstream drainage areas used to estimate grid square ratios, and areas used twice.

The hydrometric stations' drainage areas did not, in general coincide with the grid square boundaries, but an acceptable approximation was made. Since several stations were used to calculate the ratios, they were weighted both by the gross drainage areas involved and by the subjectively estimated fraction of the gross drainage area contained in a particular grid square (see Table 3 column named "% in Grid Square").

The dead drainage basin areas were as assumed in Figure A3-1. This is inaccurate according to Energy, Mines and Resources (1985). However, the discrepancy between the assumed and actual areas should produce acceptable errors on individual grid square ratios, while overall for the basin there will be little error introduced. The only error introduced for the basin as a whole is the assumption that the assumed portion of hydrometric station area 5KA (the Middle Lake / Lake Lenore basin) is the dead drainage area within the Saskatchewan River basin, and comparison with Energy, Mines and Resources (1985) shows that this area was well delineated.

A subjectively assessed uncertainty was assigned to each drainage area ratio.

Table 3--Drainage Ratio Calculations

Approximate Drainage Region	Drainage Station	Drainage Area (sq')	Effective Drainage Area (sq')	Hydrologic Station	Drainage Area (sq')	Effective Drainage Area (sq')	Ratio	% in Grid	Gross Area Effective area Grid Square	Subjectively Estimated
Region	Station Name	Area (sq')	Area (sq')	Station Name	Area (sq')	Area (sq')			Ratio	Uncertainty
(SA) a-b-c+d-e-f	SAC006	27508	21310	SAF dead basin	0	0	.77	.90	24757	99179
	SAC023	3919	3490		0	0	.74	1	3919	3490
(SB) A to B	SAB004	20270	18120	none	0	0	.89	1	20270	18120
(SC) a-b-e	SCB001	2544	2471	none	0	0	.96	1	2544	2471
	SCA010	3459	3459	none	0	0	1	1	3459	3459
	SCB007	1889	999	none	0	0	.95	1	1889	999
	SCB005	3584	2434	none	0	0	.68	1	3584	2434
	SCB002	2426	2158	none	0	0	.89	1	2426	2158
TOTAL										
for S0115 grid square:		66799	54441		0	0	.81		66848	52310
										.82 ± 0.05
SD	SDF001	28014	27337	none	0	0	.98	1	28014	27337
SEC	SEC001	1788	1489	none	0	0	.83	1	1788	1489
	SEC002	11993	11130	SCB001	2544	2471	.95	1	9029	8659
	"	0	0	SCA010	3459	3459	1	1	-3459	-3459
SED	none avail.	0	0	none avail.	0	0	0	0	0	0
(SE) a-b	SEA001	3350	2488	none	0	0	.74	1	3350	2488
	SEB008	2070	1292	none	0	0	.62	.90	1863	1183
SEC	none avail.	0	0	none avail.	0	0	0	0	0	0
SFA	SFA006	7237	3864	none	0	0	.53	1	7237	3864
TOTAL										
for S4115 grid square:		54052	47600		6823	3950	.87		47822	41541
										.87 ± 0.05
(SA) G to H - SBA - (SC) D-F to E - (SH) B to F	SAC004	135548	86985	SAB006	27508	21310	.52	.90	97234	59188
"	0	0	0	SAB004	20270	18120	.90		-16243	-16308
"	0	0	0	SCB007	1889	999	.90		-962	-899
"	0	0	0	SCB005	3584	2434	.68		-3226	-2191
"	0	0	0	SCB002	2426	2158	.89		-2183	-1962
SHC	SAC007	3912	2642	none	0	0	.68	1	3912	2642
SBA - SGB	dead basin	25152	0	none	0	0	0	.54	14881	0
SBA	dead basin	13755	0	none	0	0	0	1	13755	0
SAI	dead basin	9318	0	none	0	0	0	1	9318	0
TOTAL										
for S0110 grid square:		183685	89637		54257	43021	.35		199687.90	48410
										.37 ± 0.10
(SE) C-D-E-F-G - (SF) B-C-D-E-F - SEC - SGB	SAB001	119241	67963	SFA006	7237	3864	.42	.95	108404	60894
"	0	0	0	SEC003	1491	1880	1		-1491	-1880
"	0	0	0	SAB004	720	586	1		-720	-586
"	0	0	0	SEA001	3350	2488	1		-3350	-2488
"	0	0	0	SDF001	28014	27337	1		-28014	-27337
SGB - SGB	dead basin	25152	0	none	0	0	0	.43	10982	0
TOTAL										
for S4110 grid square:		144395	67963		48812	35335	.31		83790.80	39423.05
										.35 ± 0.05
(SH) C-D-E-F	SAC004	135548	86985	SAB001	119425	68254	.33	.30	4864	2019
"	0	0	0	SAB007	3912	2642	.30		-1176	-793
SHC	SAB001	141219	88234	SAC004	135548	86985	.22	.80	4537	990
TOTAL										
for S0105 grid square:		276767	175219		25863	16983	.30		8207	2225
										.27 ± 0.10
SBA	dead basin	2534	0	none	0	0	0	1	2224	0
(SC) G-H-G - SBA - (SA) A to B	SCB008	327663	286423	SAB001	119241	67963	.75	.88	166736	110768
"	0	0	0	SAB001	141219	88234	1		-141219	-88234
TOTAL										
for S4105 grid square:		329887	286423		260460	196197	.72		27742.60	22534
										.81 ± 0.1
(SC) G-H-J	SCB001	347267	223907	SCB008	327663	286423	.89	.70	13723	12239
TOTAL										
for S4188 grid square:		347267	223907		327663	286423	.89		13723	12239
										.89 ± 0.1

Explanation

The sub-sub-divisional designations referred to under "Approximate Drainage Region" are from the map of the Prairie Provinces' Active Hydrologic Stations (1977). The use of square brackets denotes that the several sub-sub-division letter designations have the sub-divisional and divisional designations specified within the brackets.

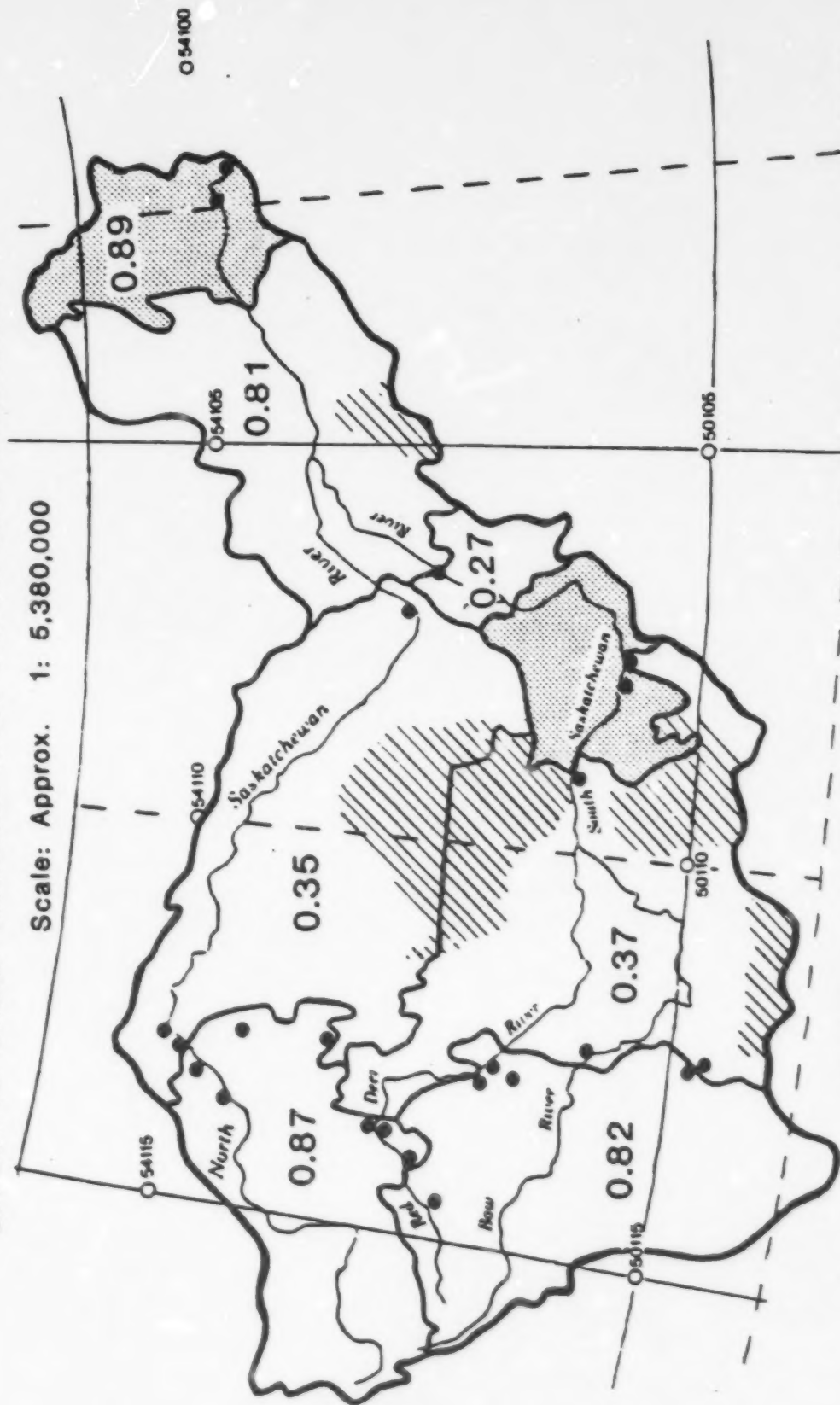
These drainage areas are abstracted from "The Determination of Gross and Effective Drainage Areas in the Prairie Provinces" hydrology report #704 Rev 1983 issued by the Prairie Farm Rehabilitation Administration, Overlay Division, Regina, Saskatchewan.

Note that the drainage areas for each hydrologic station do not correspond with the boundaries of the sub-sub-divisions in general. An exact appraisal of the areas represented by the calculations can only be made with reference to the hydrologic stations themselves and not the Prairie Provinces' Active Hydrologic Stations map.

LOS MASH
February 1, 1988

POTENTIAL IMPACT OF FUTURE CLIMATIC CHANGE
ON THE SASKATCHEWAN RIVER BASIN PROJECT
EFFECTIVE-GROSS DRAINAGE AREA RATIOS (NOT NORMALIZED)

Scale: Approx. 1: 5,380,000



-  Dead basin in SRB
-  Area used twice
-  Approximate location of hydrometric stations

FIGURE A3-1

Calculation of Effective Drainage Areas for Each Grid Square

Table 4 shows the normalized effective drainage areas for each grid square as calculated from Table 3 estimated effective to gross-gross drainage area ratios for each grid square.

The planimetered grid square areas were multiplied by each square's ratio to get the effective drainage area; then the effective areas were summed to obtain a total effective drainage area (based on planimetric readings) of 250997.7 km². The total effective drainage area established by PRFA (1986) for the Saskatchewan River basin at hydrometric station at The Pas is 223906.5 km². The ratio $223906.5/250997.7 = 0.8921$ was factored into the ratios to obtain the normalized effective/gross-gross drainage area ratios in Table 4. These normalized ratios (to a much greater precision than the two significant figures displayed in Table 4) were in turn factored into the grid square planimetered areas to obtain the normalized effective drainage areas for each grid square.

The uncertainty assigned in Table 3 was used to produce the uncertainty listed for each grid square in Table 4. This uncertainty is intended to account only for errors made in the representation of the grid squares by drainage areas listed in PFRA (1986) for hydrometric stations. It does not account for the unknown level of uncertainty associated with the effective drainage area estimates for hydrometric stations in PFRA (1986).

Table 4--Effective Drainage Areas for Each Grid Square

Grid Point	NORMALIZED Effective/Gross-Gross Drainage Area Ratio	NORMALIZED Effective Drainage Area in each Grid Square (km ²)	Uncertainty (km ²)
50°N 105°W	0.24	3565	± 1300
50°N 110°W	0.33	33166	± 9000
50°N 115°W	0.73	52296	± 3200
54°N 115°W	0.78	43386	± 2500
54°N 110°W	0.31	23766	± 3400
54°N 105°W	0.72	55252	± 6800
54°N 100°W	0.79	12476	± 1400
Totals:		223907	

Actual from hydrometric station 5KJ001 (Saskatchewan River at The Pas) is 223906 km².

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Appendix 4

Thorntwaite Program

APPENDIX 4--Thornthwaite Program

```
// JOB
//STEP1 EXEC FORTVCLG,FVLVL=66
//FORT.SYSIN DD *
C
C
C  NORMAL MONTHLY THORNTWHAITE WATER BUDGET
C
C  MWB
C
C
C *****
C *****
C
C  MAIN PROGRAM FOR MONTHLY WATER BUDGET
C
C  VERSION 1.0          PYT LOUIE
C                      ACHP
C                      FEB, 1979
C
C *****
C
C
C  THIS IS A NORMAL MONTHLY WATER BUDGET PROGRAM.
C  WATER BUDGET CALCULATION ARE BASED ON THE METHOD BY THORNTWHAITE.
C
C  THE MAIN PROGRAM HANDLES ALL I/O FUNCTIONS.WATER BUDGET
C  CALCULATIONS ARE DONE IN THE SUBROUTINE MWB WHICH IN TURN
C  REQUIRES THE SUBROUTINES: SMELT,EVAP,DAYLEN.
C
C
C  STATIONS PARAMETERS REQUIRED ARE:
C
C      STN  = STATION NAME
C      L1,L2=STATION LATITUDE DEGREE-MINUTE
C      WMC  =SOIL WATER HOLDING CAPACITY
C      HI   =HEAT INDEX
C
C
C  CONSECUTIVE MONTHLY VALUES REQUIRED ARE:
C
C      T    = MEAN MONTHLY TEMPERATURE °C
C      R    = TOTAL MONTHLY RAIN
C      S    = TOTAL MONTHLY SNOWFALL IN WATER EQUIVALENT UNITS
C
C  THESE MONTHLY VALUES TOGETHER WITH THE MONTH-YEAR ARE STORED IN
C  HOLDING ARRAYS: TT,RR,SS,MO,IY
C      WATER BUDGET COMPUTATIONS BEGIN WHEN 36 MONTHS OF DATA HAS BEEN
C  ENTERED OR  AN END OF DATA SET HAS BEEN INDICATED
C
C
```

```

C WATER BUDGET COMPONENTS ARE CONTAINED IN THE BUDGET ARRAY:
C
C     BUDGET(1)=MEAN MONTHLY TEMPERATURE
C     BUDGET(2)=TOTAL MONTHLY RAINFALL
C     BUDGET(3)=TOTAL MONTHLY SNOWFALL
C     BUDGET(4)=TOTAL MONTHLY PRECIPITATION
C     BUDGET(5)=SNOW STORAGE
C     BUDGET(6)=SNOW MELT
C     BUDGET(7)=POTENT. EVAP.
C     BUDGET(8)=RAIN+SNOWMELT-POT. EVAP.
C     BUDGET(9)=ACTUAL EVAP.
C     BUDGET(10)=SOIL MOISTURE CONTENT
C     BUDGET(11)=SOIL MOIST. CHANGE
C     BUDGET(12)=MOISTURE DEFICIT
C     BUDGET(13)=SURPLUS WATER
C
C
C .....
C
C
C     DIMENSION STN(7),BUDGET(13),TT(12),RR(12),SS(12),MO(12),IV(12),
C     +PP(12),SUM(13)
C
C INPUT STATION PARAMETERS
C
100 READ(5,1,END=700)(STN(I),I=1,7)
    1 FORMAT(7A4)
10 READ(5,*) L1,L2,WHC
    DLAT=FLOAT(L1)+(FLOAT(L2))/60.0
    SM=WHC
    SNOW=0.0
    SURP=0.0
    IYEAR=1
20 READ(5,*)(TT(J),J=1,12)
    READ(5,*)(PP(J),J=1,12)
    DO 30 J=1,12
        RR(J)=0.0
        SS(J)=0.0
        IF(TT(J).LT.0.0) SS(J)=PP(J)
        IF(TT(J).GE.0.0) RR(J)=PP(J)
30 CONTINUE
    NI=0.0
    DO 40 J=1,12
        IF(TT(J).LE.0.0) GO TO 40
        NI=NI+(TT(J)/5.0)**1.514
40 CONTINUE
C
C PRINT STATION PARAM.,INIT. VALUES,AND HEADINGS
C
C     IF(IYEAR.NE.1) GO TO 41
C     WRITE (6,18)
18 FORMAT(1H1)
41 CONTINUE
    WRITE(6,16)(STN(I),I=1,7)

```

```

16  FORMAT(1H0,7A4,1BX, '*** NORMAL MONTHLY WATER BUDGET ***')
    WRITE(6,17)L1,L2,WMC,HI
17  FORMAT(1X,'LATITUDE.....',2I3/1X,
+ 'WATER HOLDING CAPACITY...',F6.2,' MM'/1X,
+ 'HEAT INDEX.....',F6.2/)
C
C
    WRITE(6,19)
19  FORMAT(82X,'SOIL'/32X,'TOTAL SNOW SNOW',23X,'SOIL MOIST',17X
+ /1X,' MONTH TEMP RAIN SNOW PCPN STORE MELT ',
+ ' PE P-PE AE MOIST CHANGE DEF SURP '/)
C
42  DO 45 I=1,13
45  SUM(I)=0.0
    SSTOR=0.0
C
    DO 50 IT=1,6
    DO 50 J=1,12
        MON=J
        TM=TT(J)
        R=RR(J)
        S=SS(J)
C
        CALL MWB(MON,TM,R,S,SNOW,SM,SURP,WMC,DLAT,HI,BUDGET)
        IF(IT.LT.6) GO TO 50
C
        DO 46 I=1,13
46  SUM(I)=SUM(I)+BUDGET(I)
        IF(BUDGET(5).GT.SSTOR) SSTOR=BUDGET(5)
C
C PRINT BUDGET COMPONENTS
C
    WRITE(6,21)MON,(BUDGET(K),K=1,13)
21  FORMAT(6X,13,13F7.1)
50  CONTINUE
C
    SUM(1)=SUM(1)/12.0
    SUM(5)=SSTOR
    WRITE(6,23) (SUM(I),I=1,9),(SUM(I),I=12,13)
23  FORMAT(/1X,'ANNUAL',2X,9F7.1,14X,2F7.1///)
C
60  IYEAR=IYEAR+1
    IF(IYEAR.EQ.3) IYEAR=1
    GO TO 100
700 CONTINUE
    STOP
    END
C
C
C
C
C
C

```

```

C MONTHLY WATER BUDGET SUBROUTINE
C
C
C METHOD
C CALCULATIONS ARE BASED ON THE THORNTWHAITE WATER BUDGET
C
C SUBROUTINES ARE REQUIRED TO CALCULATE THE SNOWMELT AND
C POTENTIAL EVAPOTRANSPIRATION COMPONENTS
C
C
C
C SUBROUTINE MMB(MON,TM,R,S,SNOW,SM,SURP,WHC,DLAT,HI,BUDGET)
C
C
C
C MON=MONTH
C TM=MEAN MONTHLY TEMPERATURE °C
C R=TOTAL MONTHLY RAIN
C S=TOTAL MONTHLY SNOW IN WATER EQUIVALENT UNITS
C SNOW=SNOW STORAGE IN WATER EQUIVALENT UNITS
C SHI=PREVIOUS MONTH'S SOIL MOISTURE
C SM=CURRENT MONTH'S SOIL MOISTURE
C SURP=SURPLUS WATER AVAILABLE FOR NEXT MONTH'S RUN-OFF
C WHC=WATER HOLDING CAPACITY OF SOIL
C RLAG=RUN-OFF LAG FACTOR
C DLAT=LATITUDE IN DECIMAL DEGREES
C HI=HEAT INDEX
C SMELT=SNOW MELT IN WATER EQUIVALENT UNITS
C PE=POTENTIAL EVAPOTRANSPIRATION
C AE=ACTUAL EVAPOTRANSPIRATION
C DSM=SOIL MOISTURE CHANGE
C DEF=MOISTURE DEFICIT
C RO=RUN-OFF
C
C BUDGET=ARRAY CONTAINING WATER BUDGET COMPONENTS
C
C
C
C
C DIMENSION BUDGET(13)
C
C
C SHI=SM
C
C
C IF(TM.GT.0.0) GO TO 10
C PE=0.0
C SMELT=0.0
C SNOW=SNOW+S
C GO TO 40
10 CONTINUE
C
C IF(SNOW.GT.0.0) GO TO 20
C SMELT=0.0
C GO TO 30

```

```

20  CALL MELT(TM,SNOW,SMELT)
30  CALL EVAP(NON,DLAT,TM,NI,PE)
C
40  PMPE=R+SMELT-PE
    IF(PMPE.GE.0.0) GO TO 50
    SM=SMI*((2.0*WMC+PMPE)/(2.0*WMC-PMPE))
    AE=R+SMI-SM
    SURP=0.0
    GO TO 60
50  AE=PE
    SM=SMI+PMPE
60  IF(SM.LT.WMC) GO TO 70
    SURP=SM-WMC
    SM=WMC
70  DSM=SM-SMI
    DEF=AE-PE
C
C
    BUDGET(1)=TM
    BUDGET(2)=R
    BUDGET(3)=S
    BUDGET(4)=R+S
    BUDGET(5)=SNOW
    BUDGET(6)=SMELT
    BUDGET(7)=PE
    BUDGET(8)=PMPE
    BUDGET(9)=AE
    BUDGET(10)=SM
    BUDGET(11)=DSM
    BUDGET(12)=DEF
    BUDGET(13)=SURP
    RETURN
    END
C
C
C
C
C
C
C SNOWMELT SUBROUTINE
C
C
C METHOD
C ASSUMES TOTAL MELT OF SNOWPACK IF MEAN MONTHLY TEMPERATURE
C IS ABOVE 0°C
C
    SUBROUTINE MELT(TM,SNOW,SMELT)
C
    IF(TM.LE.0.0) GO TO 10
    SMELT=SNOW
    SNOW=0.0
10  RETURN
    END
C

```



```

MM=MD(M)
XM=MM
TOT=0.0
DO 300 I=1,MM
DAY=I
DAY=DM(M)+DAY
THETA=DAY*6.2832/365.0
SUM=A(1)
DO 20 J=1,4
FACT=J
SUM=(SIN(THETA*FACT))*A(J+1) + SUM
20 SUM=(COS(THETA*FACT))*B(J) + SUM
D=0.0174529*SUM
IF(DLAT.LT.0.0) D=-D
ALTIT=DLAT*.0174529
IF (D) 212,215,214
212 CWT=-SIN(D)/COS(D)*(SIN(ALTIT)/COS(ALTIT))
CDA = 1.-CWT**2
IF (CDA.GE.0) GO TO 213
CDA = ABS(CDA)
TWT = - SQRT(CDA)/CWT
GO TO 211
213 TWT = SQRT (1.-CWT**2)/CWT
211 T = ATAN(TWT)/.2618
GO TO 218
214 CWT=-SIN(D)/COS(D)*(SIN(ALTIT)/COS(ALTIT))
CDA = 1.-CWT**2
IF (CDA.GE.0) GO TO 217
CDA = ABS(CDA)
TWT = - SQRT(CDA)/CWT
GO TO 219
217 TWT = SQRT (1.-CWT**2)/CWT
219 T=(3.1416+ATAN(TWT))/.26175
GO TO 218
215 T=6.
218 IF(T.LT.0.0) T=0.0
IF(T.GT.12.0) T=12.0
TOT=TOT+2.0*T/12.0
300 CONTINUE
DAYL=TOT/XM
RETURN
END
/*
//GO.SYSIN DD *
CENTRAL ALBERTA, NORMAL
54 00 100
-17.0 -10.0 -6.0 3.0 9.5 13.5 15.6 14.4 9.4 4.8 -5.0 -12.7
24.8 19.8 18.6 21.0 43.4 87.0 86.8 77.5 33.0 15.5 24.0 24.8
CENTRAL ALBERTA, OSUB7, 2XCO2
54 00 100
-14.6 -6.8 -4.3 7.0 12.7 17.3 19.8 17.3 12.1 7.2 -1.1 -10.9
24.8 21.2 18.6 25.2 47.7 83.5 71.2 84.5 44.9 13.3 29.0 24.8
CENTRAL ALTA-SASK BORDER, NORMAL
54 00 100

```

-19.8 -14.5 -8.5 3.0 10.5 14.2 16.6 15.2 9.7 4.0 -7.0 -15.0
 21.7 17.0 18.6 18.0 40.3 78.0 80.6 65.1 42.0 15.5 15.0 21.7
 CENTRAL ALTA-SASK BORDER, OSU87, 2XCO2
 54 00 100
 -16.7 -11.0 -6.1 7.2 13.5 17.5 20.4 18.0 12.9 6.1 -3.1 -12.8
 27.1 19.8 20.1 21.8 42.3 81.9 80.6 78.1 49.6 15.5 17.6 25.6
 CENTRAL SASKATCHEWAN, NORMAL
 54 00 100
 -22.3 -17.0 -9.5 1.5 9.5 14.5 17.0 15.2 9.5 3.5 -8.0 -16.5
 18.6 14.1 21.7 21.0 40.3 72.0 80.6 52.7 51.0 27.9 27.0 24.8
 CENTRAL SASKATCHEWAN, OSU87, 2XCO2
 54 00 100
 -18.6 -13.2 -6.5 5.4 12.5 17.8 20.6 18.0 12.9 5.8 -4.5 -13.9
 24.2 16.7 25.4 25.2 36.7 75.6 75.0 62.2 55.1 33.5 31.1 29.8
 WEST CENTRAL MANITOBA, NORMAL
 54 00 100
 -23.5 -19.0 -11.5 -0.5 8.0 13.5 17.7 16.0 9.6 3.5 -7.8 -18.0
 18.6 17.0 24.8 24.0 37.2 60.0 71.3 58.9 57.0 34.1 36.0 24.8
 WEST CENTRAL MANITOBA, OSU87, 2XCO2
 54 00 100
 -19.3 -14.8 -8.0 3.0 11.1 17.2 21.1 19.1 13.1 6.0 -4.9 -14.8
 22.7 20.0 33.7 28.8 33.9 70.8 71.3 74.8 61.6 44.3 43.2 24.8
 S ALTA-BC BORDER, NORMAL
 50 00 100
 -10.5 -7.5 -5.0 4.0 11.7 10.0 13.0 13.0 9.0 3.5 -5.0 -7.5
 99.2 53.7 49.6 51.0 49.6 75.0 46.5 55.8 45.0 49.6 51.0 99.2
 (adjusted S-ALTA-BC border normals--M&S pcpr. x 0.690)
 -10.5 -7.5 -5.0 4.0 11.7 10.0 13.0 13.0 9.0 3.5 -5.0 -7.5
 68.4 37.0 34.2 35.2 34.2 51.8 32.1 38.5 31.1 34.2 35.2 68.4
 S ALTA-BC BORDER, OSU87, 2XCO2
 50 00 100
 -8.6 -4.8 -3.4 7.7 14.4 13.4 16.2 15.3 11.6 5.5 -1.3 -5.6
 108.1 58.5 57.5 67.3 51.6 91.5 41.9 69.8 50.9 41.2 55.6 104.2
 S ALTA-SASK BORDER, NORMAL
 50 00 100
 -12.0 -8.5 -4.0 4.0 11.0 16.4 19.2 19.0 13.0 6.0 -2.0 -9.0
 21.7 22.6 15.5 39.0 43.4 63.0 43.4 43.4 36.0 18.6 18.0 24.8
 S ALTA-SASK BORDER, OSU87, 2XCO2
 50 00 100
 -9.3 -5.6 -1.8 8.1 13.7 19.3 22.4 21.3 16.0 7.7 1.7 -6.8
 28.9 24.0 17.5 51.1 43.4 71.2 46.0 49.9 41.4 18.6 20.3 28.0
 S SASKATCHEWAN, NORMAL
 50 00 100
 -17.0 -12.5 -6.5 4.5 10.7 16.2 19.0 19.0 12.0 6.0 -4.5 -11.5
 18.6 19.8 21.7 30.0 49.6 75.0 49.6 46.5 39.0 18.6 18.0 18.6
 S SASKATCHEWAN, OSU87, 2XCO2
 50 00 100
 -13.4 -9.3 -3.4 8.4 13.7 19.5 22.2 21.7 15.4 7.9 -1.1 -9.0
 25.3 21.4 26.7 39.3 47.6 71.3 64.0 60.9 39.0 22.0 21.1 20.1
 END OF FILE*****
 /*
 //

APPENDIX 5--Climatic Warming Scenario Data

The scenarios of climatic warming under a doubled concentration of carbon dioxide were developed for the seven Goddard Institute for Space Studies (GISS) GCM grid-points covering the Saskatchewan River basin in the following manner.

For temperature:

- 1) Hengeveld and Street's (1986) grid-point normals corresponding to the GISS GCM grid were used as the 1 x CO₂ temperatures;
- 2) The change in mean grid-point temperature from the 1 x CO₂ to the 2 x CO₂ GCM runs, where the temperatures were interpolated to the GISS GCM grid as necessary, was added to the Hengeveld and Street (1986) normals to produce the 2 x CO₂ scenarios for the current study.

For precipitation:

- 1) Hengeveld and Street's (1986) grid-point normals corresponding to the GISS GCM grid were multiplied by the average number of days in a month to produce a monthly normal precipitation, with a precision of 0.1 millimetre/month, from the daily average value for the month recorded by Hengeveld and Street, to a precision of 0.1 millimetre/day.
- 2) The fractional change in mean grid-point precipitation from the 1 x CO₂ to the 2 x CO₂ GCM runs, where the precipitation values were interpolated to the GISS GCM grid as necessary, was multiplied into the Hengeveld and Street (1986) normals and added to them to produce the 2 x CO₂ scenarios for the current study.

The 2 x CO₂ values are accompanied by the Hengeveld and Street (1986) normals in the following tables for each of the seven grid points in the five model scenarios.

Oregon State University GCM (1987) Scenarios for the Saskatchewan
River Basin (GISS grid-points)

Grid-point location		Month											
		Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
50°N 105°W													
Hengeveld-Street	precipitation (mm)	18.6	19.8	21.7	30.0	49.6	75.0	49.6	46.5	39.0	18.6	18.0	18.6
normal	temperature (°C)	-17.0	-12.5	-6.5	4.5	10.7	16.2	19.0	19.0	12.0	6.0	-4.5	-11.5
2xCO ₂	precipitation (mm)	25.3	21.4	26.7	39.3	47.6	71.3	64.0	60.9	39.0	22.0	21.1	20.1
scenario	temperature (°C)	-13.4	-9.3	-3.4	8.4	13.7	19.5	22.2	21.7	15.4	7.9	-1.1	-9.0
50°N 110°W													
Hengeveld-Street	precipitation (mm)	21.7	22.6	15.5	39.0	43.4	63.0	43.4	43.4	36.0	18.6	18.0	24.8
normal	temperature (°C)	-12.0	-8.5	-4.0	4.0	11.0	16.4	19.2	19.0	13.0	6.0	-2.0	-9.0
2xCO ₂	precipitation (mm)	28.9	24.0	17.5	51.1	43.4	71.2	46.0	49.9	41.4	18.6	20.3	28.0
scenario	temperature (°C)	-9.3	-5.6	-1.8	8.1	13.7	19.3	22.4	21.3	16.0	7.7	1.7	-6.8
50°N 115°W													
Hengeveld-Street	precipitation (mm)	99.2	53.7	49.6	51.0	49.6	75.0	46.5	55.8	45.0	49.6	51.0	99.2
normal	temperature (°C)	-10.5	-7.5	-5.0	4.0	11.7	10.0	13.0	13.0	9.0	3.5	-5.0	-7.5
2xCO ₂	precipitation (mm)	108.1	58.5	57.5	67.3	51.6	91.5	41.9	69.8	50.9	41.2	55.6	104.2
scenario	temperature (°C)	-8.6	-4.8	-3.4	7.7	14.4	13.4	16.2	15.3	11.6	5.5	-1.3	-5.6
54°N 100°W													
Hengeveld-Street	precipitation (mm)	18.6	17.0	24.8	24.0	37.2	60.0	71.3	58.9	57.0	34.1	36.0	24.8
normal	temperature (°C)	-23.5	-19.0	-11.5	-5	8.0	13.5	17.7	16.0	9.6	3.5	-7.8	-18.0
2xCO ₂	precipitation (mm)	22.7	20.0	33.7	28.8	33.9	70.8	71.3	74.8	61.6	44.3	43.2	24.8
scenario	temperature (°C)	-19.3	-14.8	-8.0	3.0	11.1	17.2	21.1	19.1	13.1	6.0	-4.9	-14.8
54°N 105°W													
Hengeveld-Street	precipitation (mm)	18.6	14.1	21.7	21.0	40.3	72.0	80.6	52.7	51.0	27.9	27.0	24.8
normal	temperature (°C)	-22.3	-17.0	-9.5	1.5	9.5	14.5	17.0	15.2	9.5	3.5	-8.0	-16.5
2xCO ₂	precipitation (mm)	24.2	16.7	25.4	25.2	36.7	75.6	75.0	62.2	55.1	33.5	31.1	29.8
scenario	temperature (°C)	-18.6	-13.2	-6.5	5.4	12.5	17.8	20.6	18.0	12.9	5.8	-4.5	-13.9
54°N 110°W													
Hengeveld-Street	precipitation (mm)	21.7	17.0	18.6	18.0	40.3	78.0	80.6	65.1	42.0	15.5	15.0	21.7
normal	temperature (°C)	-19.8	-14.5	-8.5	3.0	10.5	14.2	16.6	15.2	9.7	4.0	-7.0	-15.0
2xCO ₂	precipitation (mm)	27.1	19.8	20.1	21.8	42.3	81.9	80.6	78.1	49.6	15.5	17.6	25.6
scenario	temperature (°C)	-16.7	-11.0	-6.1	7.2	13.5	17.5	20.4	18.0	12.9	6.1	-3.1	-12.8
54°N 115°W													
Hengeveld-Street	precipitation (mm)	24.8	19.8	18.6	21.0	43.4	87.0	86.8	77.5	33.0	15.5	24.0	24.8
normal	temperature (°C)	-17.0	-10.0	-6.0	3.0	9.5	13.5	15.6	14.4	9.4	4.8	-5.0	-12.7
2xCO ₂	precipitation (mm)	24.8	21.2	18.6	25.2	47.7	83.5	71.2	84.5	44.9	13.3	29.0	24.8
scenario	temperature (°C)	-14.6	-6.8	-4.3	7.0	12.7	17.3	19.8	17.3	12.1	7.2	-1.1	-10.9

Geophysical Fluid Dynamics Laboratory GCM (1980) Scenarios for
the Saskatchewan River Basin (GISS grid-points)

Grid-point		Month											
location		Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
50°N 105°W													
Hengeveld-Street	precipitation (mm)	18.6	19.8	21.7	30.0	49.6	75.0	49.6	46.5	39.0	18.6	18.0	18.6
normal	temperature (°C)	-17.0	-12.5	-6.5	4.5	10.7	16.2	19.0	19.0	12.0	6.0	-4.5	-11.5
2xCO ₂	precipitation (mm)	19.0	17.3	21.4	41.3	65.3	131.7	61.3	72.4	34.0	26.3	19.5	23.6
scenario	temperature (°C)	-15.7	-11.4	-3.4	9.1	14.9	17.5	19.2	18.7	13.2	8.3	-1.6	-10.5
50°N 110°W													
Hengeveld-Street	precipitation (mm)	21.7	22.6	15.5	39.0	43.4	63.0	43.4	43.4	36.0	18.6	18.0	24.8
normal	temperature (°C)	-12.0	-8.5	-4.0	4.0	11.0	16.4	19.2	19.0	13.0	6.0	-2.0	-9.0
2xCO ₂	precipitation (mm)	20.4	18.2	16.6	43.6	59.0	92.3	33.7	73.4	33.3	16.2	19.0	17.7
scenario	temperature (°C)	-13.2	-8.8	-1.9	10.5	14.2	16.0	18.7	18.9	13.0	8.3	-1.0	-8.2
50°N 115°W													
Hengeveld-Street	precipitation (mm)	99.2	53.7	49.6	51.0	49.6	75.0	46.5	55.8	45.0	49.6	51.0	99.2
normal	temperature (°C)	-10.5	-7.5	-5.0	4.0	11.7	10.0	13.0	13.0	9.0	3.5	-5.0	-7.5
2xCO ₂	precipitation (mm)	25.7	18.7	17.6	40.3	52.8	78.7	28.0	70.2	33.2	15.9	22.4	23.8
scenario	temperature (°C)	-11.8	-7.3	-6.6	10.9	14.1	15.9	18.9	19.2	13.2	8.4	-4.4	-6.8
54°N 100°W													
Hengeveld-Street	precipitation (mm)	18.6	17.0	24.8	24.0	37.2	60.0	71.3	58.9	57.0	34.1	36.0	24.8
normal	temperature (°C)	-23.5	-19.0	-11.5	-5.5	8.0	13.5	17.7	16.0	9.6	3.5	-7.8	-18.0
2xCO ₂	precipitation (mm)	25.0	17.9	23.9	29.6	47.6	115.3	89.9	130.5	57.1	38.9	37.1	48.0
scenario	temperature (°C)	-20.7	-18.1	-8.5	2.2	8.9	14.8	18.7	15.2	10.4	4.8	-4.8	-17.5
54°N 105°W													
Hengeveld-Street	precipitation (mm)	18.6	14.1	21.7	21.0	40.3	72.0	80.6	52.7	51.0	27.9	27.0	24.8
normal	temperature (°C)	-22.3	-17.0	-9.5	1.5	9.5	14.5	17.0	15.2	9.5	3.5	-8.0	-16.5
2xCO ₂	precipitation (mm)	25.4	31.7	22.2	27.2	38.2	88.8	83.4	84.7	48.3	22.5	43.9	43.2
scenario	temperature (°C)	-21.3	-15.3	-7.1	6.6	11.1	15.8	18.1	16.6	11.7	6.2	-5.2	-15.4
54°N 110°W													
Hengeveld-Street	precipitation (mm)	21.7	17.0	18.6	18.0	40.3	78.0	80.6	65.1	42.0	15.5	15.0	21.7
normal	temperature (°C)	-19.8	-14.5	-8.5	3.0	10.5	14.2	16.6	15.2	9.7	4.0	-7.0	-15.0
2xCO ₂	precipitation (mm)	21.7	25.2	16.8	27.0	57.2	100.8	74.6	73.2	73.3	23.1	35.7	33.6
scenario	temperature (°C)	-17.7	-11.7	-3.4	9.0	13.2	14.1	16.8	17.2	12.4	7.1	-4.7	-13.2
54°N 115°W													
Hengeveld-Street	precipitation (mm)	24.8	19.8	18.6	21.0	43.4	87.0	86.8	77.5	33.0	15.5	24.0	24.8
normal	temperature (°C)	-17.0	-10.0	-6.0	3.0	9.5	13.5	15.6	14.4	9.4	4.8	-5.0	-12.7
2xCO ₂	precipitation (mm)	24.2	25.2	18.3	27.1	58.5	98.2	75.0	70.6	78.6	25.7	34.7	33.2
scenario	temperature (°C)	-16.8	-10.8	-2.9	9.3	13.8	13.9	16.5	17.2	12.4	6.9	-4.5	-12.6

Geophysical Fluid Dynamics Laboratory GCM (1987) Scenarios for
the Saskatchewan River Basin (GISS grid-points)

Grid-point location		Month											
		Jan.	Feb.	Mar.	Apr.	May	June	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
50°N 105°W													
Hengeveld-Street	precipitation (mm)	18.6	19.8	21.7	30.0	49.6	75.0	49.6	46.5	39.0	18.6	18.0	18.6
normal	temperature (°C)	-17.0	-12.5	-6.5	4.5	10.7	16.2	19.0	19.0	14.0	6.0	-4.5	-11.5
2xCO ₂	precipitation (mm)	18.6	25.9	23.7	38.4	61.0	67.5	33.2	31.6	35.9	20.1	24.1	18.6
scenario	temperature (°C)	-11.7	-5.9	.8	12.6	15.9	24.3	27.3	27.0	18.3	11.7	1.1	-5.3
50°N 110°W													
Hengeveld-Street	precipitation (mm)	21.7	22.6	15.5	39.0	43.4	63.0	43.4	43.4	36.0	18.6	18.0	24.8
normal	temperature (°C)	-12.0	-8.5	-4.0	4.0	11.0	16.4	19.2	19.0	13.0	6.0	-2.0	-9.0
2xCO ₂	precipitation (mm)	23.9	23.1	17.5	53.4	52.5	50.4	32.6	39.1	48.6	19.9	20.0	24.6
scenario	temperature (°C)	-6.7	-1.9	3.1	11.8	15.8	23.4	27.0	26.2	18.5	10.6	3.6	-3.2
50°N 115°W													
Hengeveld-Street	precipitation (mm)	99.2	53.7	49.6	51.0	49.6	75.0	46.5	55.8	45.0	49.6	51.0	99.2
normal	temperature (°C)	-10.5	-7.5	-5.0	4.0	11.7	10.0	13.0	13.0	9.0	3.5	-5.0	-7.5
2xCO ₂	precipitation (mm)	116.1	47.8	57.0	68.3	56.0	56.3	41.9	60.8	63.0	51.1	50.0	101.2
scenario	temperature (°C)	-5.1	-1.1	2.0	11.3	16.3	16.0	20.3	19.4	14.0	7.7	.5	-2.0
54°N 100°W													
Hengeveld-Street	precipitation (mm)	18.6	17.0	24.8	24.0	37.2	60.0	71.3	58.9	57.0	34.1	36.0	24.8
normal	temperature (°C)	-23.5	-19.0	-11.5	-.5	8.0	13.5	17.7	16.0	9.6	3.5	-7.8	-18.0
2xCO ₂	precipitation (mm)	23.8	20.2	28.8	29.8	30.5	57.6	57.0	61.8	68.4	40.9	45.7	30.8
scenario	temperature (°C)	-16.2	-10.7	-3.0	10.0	15.0	21.9	25.3	22.9	16.6	10.7	-1.8	-10.8
54°N 105°W													
Hengeveld-Street	precipitation (mm)	18.6	14.1	21.7	21.0	40.3	72.0	80.6	52.7	51.0	27.9	27.0	24.8
normal	temperature (°C)	-22.3	-17.0	-9.5	1.5	9.5	14.5	17.0	15.2	9.5	3.5	-8.0	-16.5
2xCO ₂	precipitation (mm)	21.9	17.5	23.2	26.3	46.3	63.4	64.5	37.9	79.1	31.2	33.5	32.2
scenario	temperature (°C)	-15.5	-9.0	-1.1	11.8	16.5	22.6	24.5	22.1	15.9	9.9	-2.5	-9.1
54°N 110°W													
Hengeveld-Street	precipitation (mm)	21.7	17.0	18.6	18.0	40.3	78.0	80.6	65.1	42.0	15.5	15.0	21.7
normal	temperature (°C)	-19.8	-14.5	-8.5	3.0	10.5	14.2	16.6	15.2	9.7	4.0	-7.0	-15.0
2xCO ₂	precipitation (mm)	26.0	19.7	21.2	23.9	50.0	87.4	66.9	50.1	58.8	16.0	17.3	25.2
scenario	temperature (°C)	-13.3	-6.3	-.2	12.7	16.6	21.5	23.8	22.1	15.2	9.7	-1.5	-7.9
54°N 115°W													
Hengeveld-Street	precipitation (mm)	24.8	19.8	18.6	21.0	43.4	87.0	86.8	77.5	33.0	15.5	24.0	24.8
normal	temperature (°C)	-17.0	-10.0	-6.0	3.0	9.5	13.5	15.6	14.4	9.4	4.8	-5.0	-12.7
2xCO ₂	precipitation (mm)	31.7	22.1	21.2	27.5	53.4	100.1	86.8	65.1	42.2	16.7	26.9	27.3
scenario	temperature (°C)	-10.5	-1.8	2.1	12.0	15.5	20.1	22.4	20.9	14.3	9.8	.6	-5.7

Goddard Institute for Space Studies GCM (1984) Scenarios for the
Saskatchewan River Basin (GISS grid-points)

Grid-point location		Month											
50°N 105°W		Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Hengeveld-Street	precipitation (mm)	18.6	19.8	21.7	30.0	49.6	75.0	49.6	46.5	39.0	18.6	18.0	18.6
normal	temperature (°C)	-17.0	-12.5	-6.5	4.5	10.7	16.2	19.0	19.0	12.0	6.0	-4.5	-11.5
2xCO ₂	precipitation (mm)	24.1	26.8	26.9	34.3	56.9	85.7	54.4	46.5	35.5	19.6	23.3	24.1
scenario	temperature (°C)	-11.0	-6.9	-1.7	8.6	14.4	19.5	22.3	23.0	17.0	11.6	1.4	-5.5
50°N 110°W													
Hengeveld-Street	precipitation (mm)	21.7	22.6	15.5	39.0	43.4	63.0	43.4	43.4	36.0	18.6	18.0	24.8
normal	temperature (°C)	-12.0	-8.5	-4.0	4.0	11.0	16.4	19.2	19.0	13.0	6.0	-2.0	-9.0
2xCO ₂	precipitation (mm)	28.6	30.9	19.7	46.0	49.8	73.8	47.5	45.0	34.4	19.5	22.7	32.6
scenario	temperature (°C)	-6.1	-3.1	.6	8.0	14.6	19.7	22.5	23.0	17.8	11.3	3.5	-3.2
50°N 115°W													
Hengeveld-Street	precipitation (mm)	99.2	53.7	49.6	51.0	49.6	75.0	46.5	55.8	45.0	49.6	51.0	99.2
normal	temperature (°C)	-10.5	-7.5	-5.0	4.0	11.7	10.0	13.0	13.0	9.0	3.5	-5.0	-7.5
2xCO ₂	precipitation (mm)	138.2	72.8	66.1	65.1	61.6	92.2	55.0	61.8	46.9	56.0	60.8	127.6
scenario	temperature (°C)	-5.3	-2.6	-1.0	7.4	14.9	13.0	16.1	16.6	12.9	7.3	-1.0	-2.8
54°N 100°W													
Hengeveld-Street	precipitation (mm)	18.6	17.0	24.8	24.0	37.2	60.0	71.3	58.9	57.0	34.1	36.0	24.8
normal	temperature (°C)	-23.5	-19.0	-11.5	-5	8.0	13.5	17.7	16.0	9.6	3.5	-7.8	-18.0
2xCO ₂	precipitation (mm)	22.1	20.9	31.0	27.6	41.7	68.8	80.2	63.1	59.4	37.5	44.5	31.0
scenario	temperature (°C)	-17.3	-13.2	-6.4	4.0	11.8	16.8	20.8	19.4	13.8	8.6	-2.0	-11.8
54°N 105°W													
Hengeveld-Street	precipitation (mm)	18.6	14.1	21.7	21.0	40.3	72.0	80.6	52.7	51.0	27.9	27.0	24.8
normal	temperature (°C)	-22.3	-17.0	-9.5	1.5	9.5	14.5	17.0	15.2	9.5	3.5	-8.0	-16.5
2xCO ₂	precipitation (mm)	24.4	19.4	28.6	25.0	47.8	84.7	93.6	54.6	53.3	30.8	35.4	32.5
scenario	temperature (°C)	-16.0	-11.4	-4.8	5.5	13.1	17.8	20.4	19.1	14.3	9.0	-2.0	-10.1
54°N 110°W													
Hengeveld-Street	precipitation (mm)	21.7	17.0	18.6	18.0	40.3	78.0	80.6	65.1	42.0	15.5	15.0	21.7
normal	temperature (°C)	-19.8	-14.5	-8.5	3.0	10.5	14.2	16.6	15.2	9.7	4.0	-7.0	-15.0
2xCO ₂	precipitation (mm)	30.6	22.6	24.2	22.2	47.8	94.1	90.7	69.9	42.0	17.9	19.2	29.4
scenario	temperature (°C)	-13.6	-9.0	-4.0	6.8	14.0	17.5	19.9	19.0	14.3	9.2	-1.2	-8.8
54°N 115°W													
Hengeveld-Street	precipitation (mm)	24.8	19.8	18.6	21.0	43.4	87.0	86.8	77.5	33.0	15.5	24.0	24.8
normal	temperature (°C)	-17.0	-10.0	-6.0	3.0	9.5	13.5	15.6	14.4	9.4	4.8	-5.0	-12.7
2xCO ₂	precipitation (mm)	33.7	27.2	24.8	26.4	54.6	107.4	100.0	85.8	35.9	17.6	29.2	33.1
scenario	temperature (°C)	-11.4	-5.1	-2.1	6.4	12.6	16.5	18.6	17.9	13.3	8.9	-.4	-7.4

Goddard Institute for Space Studies GCM (1987) Scenarios for the
Saskatchewan River Basin (GISS grid-points)

Grid-point		Month											
location		Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
50°N 105°W													
Hengeveld-Street	precipitation (mm)	18.6	19.8	21.7	30.0	49.6	75.0	49.6	46.5	39.0	18.6	18.0	18.6
normal	temperature (°C)	-17.0	-12.5	-6.5	4.5	10.7	16.2	19.0	19.0	12.0	6.0	-4.5	-11.5
2xCO ₂	precipitation (mm)	21.4	26.7	28.4	30.6	56.5	79.5	60.0	53.5	26.5	23.6	26.3	20.8
scenario	temperature (°C)	-10.9	-6.4	-1.9	9.5	14.0	19.5	21.8	22.1	18.0	10.8	1.8	-6.0
50°N 110°W													
Hengeveld-Street	precipitation (mm)	21.7	22.6	15.5	39.0	43.4	63.0	43.4	43.4	36.0	18.6	18.0	24.8
normal	temperature (°C)	-12.0	-8.5	-4.0	4.0	11.0	16.4	19.2	19.0	13.0	6.0	-2.0	-9.0
2xCO ₂	precipitation (mm)	26.9	33.4	20.5	39.4	54.7	65.5	52.9	47.7	21.6	24.4	27.4	29.3
scenario	temperature (°C)	-5.7	-2.2	-1.1	8.4	14.5	19.8	21.8	22.7	18.9	11.2	4.4	-3.4
50°N 115°W													
Hengeveld-Street	precipitation (mm)	99.2	53.7	49.6	51.0	49.6	75.0	46.5	55.8	45.0	49.6	51.0	99.2
normal	temperature (°C)	-10.5	-7.5	-5.0	4.0	11.7	10.0	13.0	13.0	9.0	3.5	-5.0	-7.5
2xCO ₂	precipitation (mm)	130.9	78.4	63.5	58.7	60.5	88.5	54.9	64.2	33.8	62.0	67.8	126.0
scenario	temperature (°C)	-4.0	-1.9	-1.3	8.1	14.9	13.4	15.4	17.0	14.2	7.8	.0	-2.5
54°N 100°W													
Hengeveld-Street	precipitation (mm)	18.6	17.0	24.8	24.0	37.2	60.0	71.3	58.9	57.0	34.1	36.0	24.8
normal	temperature (°C)	-23.5	-19.0	-11.5	-5	8.0	13.5	17.7	16.0	9.6	3.5	-7.8	-18.0
2xCO ₂	precipitation (mm)	21.9	22.4	35.5	26.9	40.5	72.0	85.6	67.7	54.7	43.0	46.8	29.0
scenario	temperature (°C)	-16.2	-12.9	-6.4	4.5	11.3	16.4	21.0	18.7	13.8	8.0	-1.2	-11.9
54°N 105°W													
Hengeveld-Street	precipitation (mm)	18.6	14.1	21.7	21.0	40.3	72.0	80.6	52.7	51.0	27.9	27.0	24.8
normal	temperature (°C)	-22.3	-17.0	-9.5	1.5	9.5	14.5	17.0	15.2	9.5	3.5	-8.0	-16.5
2xCO ₂	precipitation (mm)	22.9	19.2	31.7	23.9	46.7	85.7	98.3	58.0	44.9	36.5	36.2	29.8
scenario	temperature (°C)	-15.0	-11.2	-5.1	6.2	13.0	17.6	20.2	18.2	13.9	8.2	-1.3	-10.3
54°N 110°W													
Hengeveld-Street	precipitation (mm)	21.7	17.0	18.6	18.0	40.3	78.0	80.6	65.1	42.0	15.5	15.0	21.7
normal	temperature (°C)	-19.8	-14.5	-8.5	3.0	10.5	14.2	16.6	15.2	9.7	4.0	-7.0	-15.0
2xCO ₂	precipitation (mm)	28.0	23.9	26.0	21.1	50.0	92.0	98.3	71.6	34.9	20.9	20.6	27.8
scenario	temperature (°C)	-12.5	-8.6	-4.8	7.2	14.0	17.6	19.5	18.7	14.5	8.9	-.3	-8.8
54°N 115°W													
Hengeveld-Street	precipitation (mm)	24.8	19.8	18.6	21.0	43.4	87.0	86.8	77.5	33.0	15.5	24.0	24.8
normal	temperature (°C)	-17.0	-10.0	-6.0	3.0	9.5	13.5	15.6	14.4	9.4	4.8	-5.0	-12.7
2xCO ₂	precipitation (mm)	33.0	28.5	24.2	25.8	53.8	107.0	102.4	86.8	30.7	20.2	30.7	34.5
scenario	temperature (°C)	-9.6	-4.4	-2.8	6.9	12.8	16.7	18.3	18.1	13.7	9.1	1.2	-6.8